DETERMINING THE HORIZONTAL DISTANCE DISTRIBUTION OF CLOUD-TO-GROUND LIGHTNING

THESIS

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Abstract

Military installations, airports, sporting events, and other facilities curtail operations when cloud-to-ground (CG) lightning is present. The National Lightning Detection Network records approximately 20 million lightning flashes each year (Orville and Huffines 1999). Because of the frequency and random nature of CG lightning more people become casualties to lightning each year than to either tornadoes or hurricanes. Lightning specific warning criteria are not standard and appear to have evolved over time as a result of increasing the distance in response to lightning incidents until the proper balance between threat and impact were achieved, rather than through research and lightning data analysis. This research effort attempted to quantify what constitutes a safe distance when lightning is present.

The method used in this research project groups lightning flashes into clusters using spatial and temporal constraints. However, not all flashes meet the time and distance criteria for clustering and remained outside of the grouped flashes and as such are identified as isolated flashes. These isolated flashes are outliers in the data set, but are precisely the flashes that prove most dangerous. For this reason not only were the distances between each flash and cluster center studied, but also the distances between each isolated flash and its nearest neighboring flash. Distributions for both distances were studied for the continental U.S. by season.

A common safety radius is 5 nautical miles, just less than 9.5 km. For all regions, anywhere from 16% to 35% of the clustered flashes occurred beyond 9.5 km from the cluster center and 71% to 81% of the isolated flashes occurred at distances beyond 9.5 km from the nearest flash. Cumulative frequency distributions of historical lightning data can be used to find the probability of having lightning at a particular distance. In this way an acceptable level of risk can be determined and then a "safe" distance found.

DETERMINING THE HORIZONTAL DISTANCE DISTRIBUTION OF CLOUD-TO-GROUND LIGHTNING

1. Introduction

1.1 Background

On 29 April 1996 a routine "lightning within 3" advisory was issued at 0804 CDT at Hurlburt Field, Florida. The Base Weather Station canceled the advisory at 0930 CDT, nearly 90 minutes after the last observed lightning flash in the area, at which time airfield operations promptly resumed. At 0938 CDT a lightning flash struck the airfield killing one airman and injuring 10 others (Bauman 1998: slide 6). According to air traffic controllers, the lightning came from thunderstorms located 5 – 7 miles south of the airfield. The incident at Hurlburt Field, Florida, raised questions about the adequacy of Air Force lightning safety procedures. The Air Force Safety Agency assembled a Lightning Safety Review Panel to determine if lightning procedures were adequate and, if not, to recommend changes to better protect Air Force personnel (Bauman 1998: slide 26).

Currently the Air Force Operational Safety and Health (AFOSH) Standard 91-100 states, "A *Lightning Watch* is in effect 30 minutes prior to thunderstorms being within a 5 nautical mile radius of any pre-determined location or activity as forecast by the Base Weather Station. A *Lightning Warning* is in effect whenever any lightning is occurring within a 5 nautical mile radius of the pre-determined locations and activities." Only *Lightning Warnings* stop outside activities, not *Lightning Watches*. Procedures dictate the cessation of outside activities on Air Force bases only when lightning is actually occurring within a 5-nautical mile radius of some pre-determined location. This begs the question of whether or not the 5-nautical mile safety radius is adequate for the protection and safety of Air Force personnel and property.

Besides the Air Force, other agencies such as civilian airports, and airlines curtail activities when lightning is present. Particular sporting events such as the Professional Golf Association, and other outdoor recreational activities take precautions when thunderstorms or lightning are in the area. Lightning specific warnings do exist, but the warning criteria appear to be somewhat arbitrary and seem to exist as a result of increasing the distance in response to lightning incidents until the proper balance between threat and impact was achieved. Lightning specific warnings seem to have evolved over time rather than having through scientific research and data analysis. For this reason, objective safety criteria are needed when lightning is present.

Two previous students of the Air Force Institute of Technology (AFIT) have tackled this question. Neither found a conclusive answer nor had the time to study large quantities of data. Beyond their recent studies very little research has been done on the horizontal distance lightning travels. A nationwide network of cloud-to-ground (CG) lightning detectors has been collecting and archiving data since 1989 so it is now possible to study large quantities of data from the entire United States.

1.2. Problem statement

The primary goal of this research was to determine whether the existing Air Force 5-nautical mile stand-off criterion outlined in AFOSH 91-100 is adequate and if not what constitutes a safe distance when lightning is present. Regardless of what an absolutely safe distance is, some work will still have to be accomplished outdoors, and shutting down operations or events until the threat of lightning or lightning injury is zero is simply unrealistic. Many people believe there is "one" safe distance, but in reality the problem is more about weighing the level of acceptable risk against the operational need. By examining CG lightning strike positions in relationship to one another, distances between a flash position and a lightning cluster center or other lightning

flash would allow probabilities to be applied at different ranges. In this way historical lightning data can be used to determine how far lightning travels and compare this data to levels of risk, developing objective criteria for safe operations that balances threat and impact.

The final goal of this research was to expand the study to encompass lightning data for the entire continental United States over several years. By examining large quantities of lightning data over many locations across the continental United States over several years leads to a climotalogical type study and the possibility of determining a correlation between horizontal distance distributions and geographic areas. This could then be applied not to only military operations but also any operation or event in the country.

1.3. Implications

The National Lightning Detection Network (NLDN) recorded an average of approximately 20 million CG lightning flashes each year from 1989-98 in the continental United States (Orville and Huffines 1999). Even with a nationwide lightning detection network, no agency can forecast the exact location and time lightning flashes will strike. Because of the frequency and the random nature of CG lightning flash distributions, lightning causes more casualties than either tornadoes or hurricanes annually. According to López, et al. (1993) about 100 people are killed and more than 500 people are injured each year by lightning in the United States.

No Air Force installation in the continental United States is exempt from thunderstorms and lightning activity and for this reason lightning is a significant hazard to life, property, ground, flight, and space launch operations. Thus, safety procedures based on sound, objective meteorological reasoning must be in place to protect personnel and property. This research furthers efforts to develop these safety procedures by using archived lightning data from 1995-99

for the entire continental United States in an attempt to isolate the spatial and temporal characteristics of CG lightning patterns and determine, at least to some extent, how far lightning travels. Because this research covers the entire continental United States, those planning outdoor activities will be able to weigh the risk to personnel against operational needs, not only for the Air Force but others agencies as well.

1.4 Thesis organization

Chapter 2 sets the stage for this research with a review of relevant background literature. The methodology used to conduct the research may be found in chapter 3. Chapter 4 details results and analysis, while chapter 5 specifies conclusions from the research effort.

2. Literature Review

In order to understand how far cloud-to-ground (CG) lightning can travel, a general overview of the lightning discharge process, categories of lightning discharges, and detection of lightning discharges is necessary. Along with this information, an overview of different methods used to group lightning will be presented.

2.1 The lightning flash

Lightning is a transient, high-current electric discharge, whose path length is very tortuous and measured in kilometers (Uman 1987: 8). For lightning to occur in a thunderstorm, a separation of positively and negatively charged regions must exist and buildup until the electric field strength exceeds the breakdown potential of the atmosphere in a convective cloud. The process of charge separation in convective clouds is not fully understood and is currently an area of active research. Several theories exist, but for this thesis it is sufficient to understand there is a separation of charge in convective clouds.

Lightning discharges occur between differently charged regions and are classified in several ways. A lightning discharge inside a cloud from one charge region to another is called intracloud lightning, while lightning discharges between different clouds is called intercloud or cloud-to-cloud lightning. Cloud-to-air discharges are also possible. A lightning discharge between a cloud and the ground is referred to as cloud-to-ground lightning, and is the most widely studied even though CG lightning comprises less than half of all lightning discharges (Uman 1987: 9). Cloud-to-ground lightning is a significant hazard to life and causes damage to susceptible ground systems. Scientists can most easily study CG lightning because it is easily seen and detected. Cloud-to-ground lightning will be the subject of this research because of the hazards posed by this type of lightning.

2.1.2 Cloud-to-ground lightning discharge process

The CG lightning discharge process has several distinct components. The entire discharge process takes less than a second to complete and is called a flash (Uman 1987: 10). To start the process, sufficient charge separation must be generated in a convective cloud until the potential difference between the charge region and surrounding atmosphere reaches or exceeds the breakdown potential of the atmosphere and a coronal or point discharge is initiated from the charge region into the atmosphere (Uman 1987: 10). Figure 1(a) depicts the coronal discharge, stepped leader, and the attachment process. The discharge from the cloud is called a leader and causes an ionized path to form. The leader is approximately 50 m in length and travels at approximately 1×10^5 m s^{-1} (Idone and Orville 1982). Leaders move outward and downward in a tortuous nature. All of the leaders combined from the cloud to the ground are called a stepped leader.

As the stepped leader approaches the ground, the electric field at the surface builds until the breakdown potential is reached. This causes an upward moving discharge from the ground to occur, called the attachment leader (Uman 1987: 12). A completed circuit is made once the attachment leader and stepped leader come together, which creates path from the cloud to the ground. Charge is then transferred to the earth and a return stroke travels from the ground upward to the source region within the cloud. Figure 1(b) depicts the return stroke. The return stroke travels at approximately 2×10^8 m s^{-1} (Idone and Orville 1982) and is the brightest part of the lightning flash.

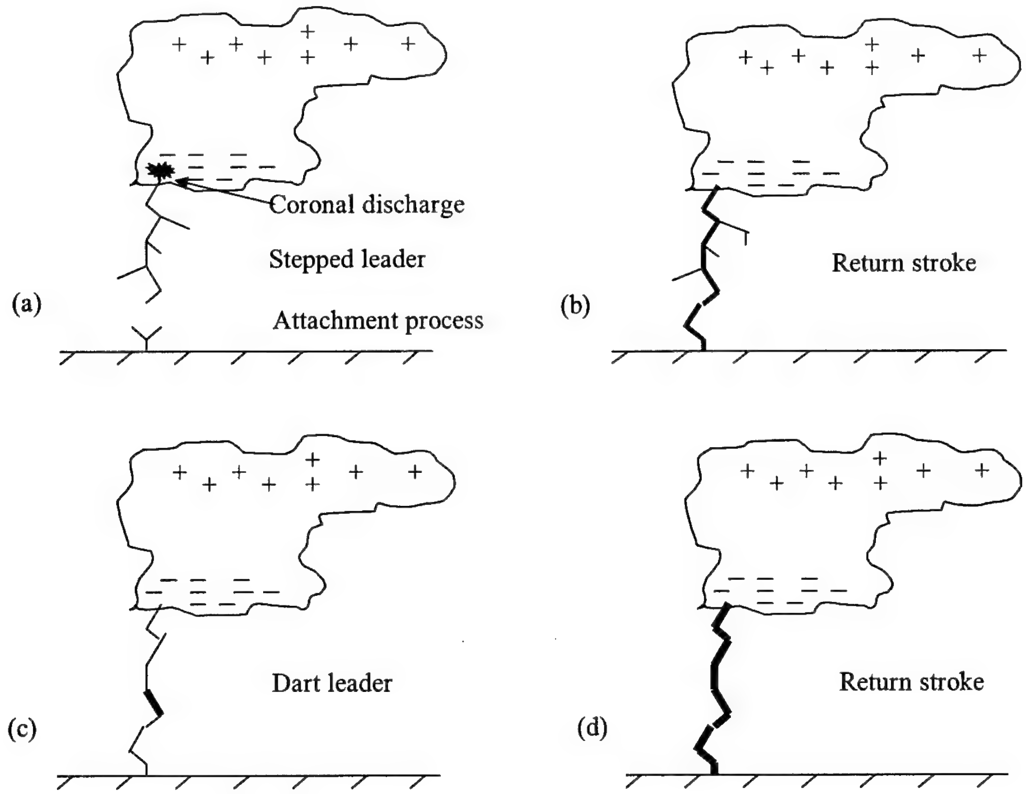

Figure 1. Cloud-to-ground lightning discharge process for a negative CG flash (Adapted from Uman, 1987: 9). In (a) the coronal discharge happens at the negative charge region followed by stepped leader propagating away from the cloud. As it approaches the ground the attachment process takes place as the upward discharge completes the channel. After this happens a return stroke occurs in (b), and moves charge from the ground back to the cloud along the main channel. In (c) the dart leader travels from cloud to ground along the main channel followed by another return stroke (d).

After the return stroke, additional discharges from the charged region may take place and follow the previously ionized path. These additional discharges are called dart leaders because they happen at a very high-speed, approximately 3 x 10^6 m s^{-1} (Uman 1987: 13). Figure 1(c) shows the high-speed dart leader. Each dart leader initiates another return stroke, as seen in Figure 1(d). This dart leader and subsequent return stroke may happen several times with the number of return strokes in a flash called the multiplicity. The discharge process, consisting of

several components from the coronal discharge to the last returns stroke usually takes less than a second to complete (Uman 1987: 10).

2.1.3 Categorization of cloud-to-ground lightning

Uman (1987: 9) classifies CG lightning into four categories according to the direction of motion of the discharge and the sign of the charge of the leader initiating the discharge. Figure 2 illustrates the four categories.

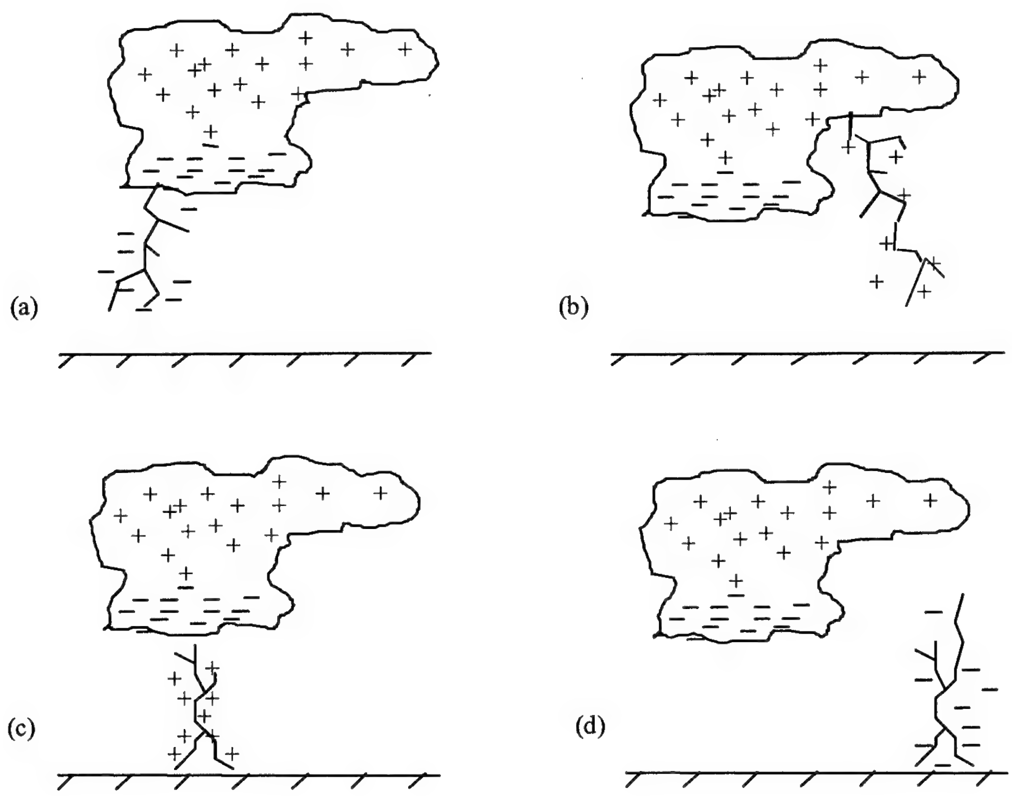

Figure 2. Categorization of four types of cloud-to-ground lightning discharges. Category (a) depicts negative cloud-to-ground lightning. Category (b) depicts positive cloud-to-ground lightning. Category (c) depicts positive ground-to-cloud lightning. Category (d) depicts negative ground-to-cloud lightning.

Figure 2 (a), negative CG lightning, is the most common type of CG lightning, and comprises 90% of all CG lightning (Uman 1987: 9). This lightning occurs when a downward moving negatively charged leader lowers negative charge to earth. Figure 2 (b) lightning is also initiated by a downward-moving charged leader but is positively charged and thus the discharge lowers positive charge to earth; however this type of lightning accounts for less than 10% of the of the CG flashes. Figure 2 (c) and (d) are upward initiated discharges from the ground to cloud; however, these flashes tend to be rare and generally occur from mountain tops and tall structures (Uman 1987: 9). Figure 2 (c) is a positively charged leader moving upwards and may lead to a lowering of negative cloud charge to the earth. Figure 2 (d) is a negatively charge leader moving upwards and may lead to a lowering of positive cloud charge to earth.

2.2 The National Lightning Detection Network

The National Lightning Detection Network (NLDN) began in 1987 when three previously independent regional networks were combined into one national network, which encompasses the entire United States (Cummins, et al. 1998). Global Atmospherics, Inc. in Tucson, Arizona, operates and controls this new network, providing real-time lightning information on a national scale, since 1989. Cummins, et al. (1998) noted the growing demands for NLDN data led to an upgrade of the network which involved combining Magnetic Detection Finders (MDF) and Time-of-Arrival (TOA) detection methods into sensors called IMPoved Accuracy from Combined Technology (IMPACT). Since the upgrade to the system, the NLDN consists of two distinct lightning detection sensors, IMPACT sensors that use both TOA and MDF technology, and sensors with only TOA capabilities. The national network consists of 59 TOA and 47 IMPACT sensors that distributed over the continental United States. Figure 3 shows the locations and combinations of the 106 sensors, which comprise the NLDN.

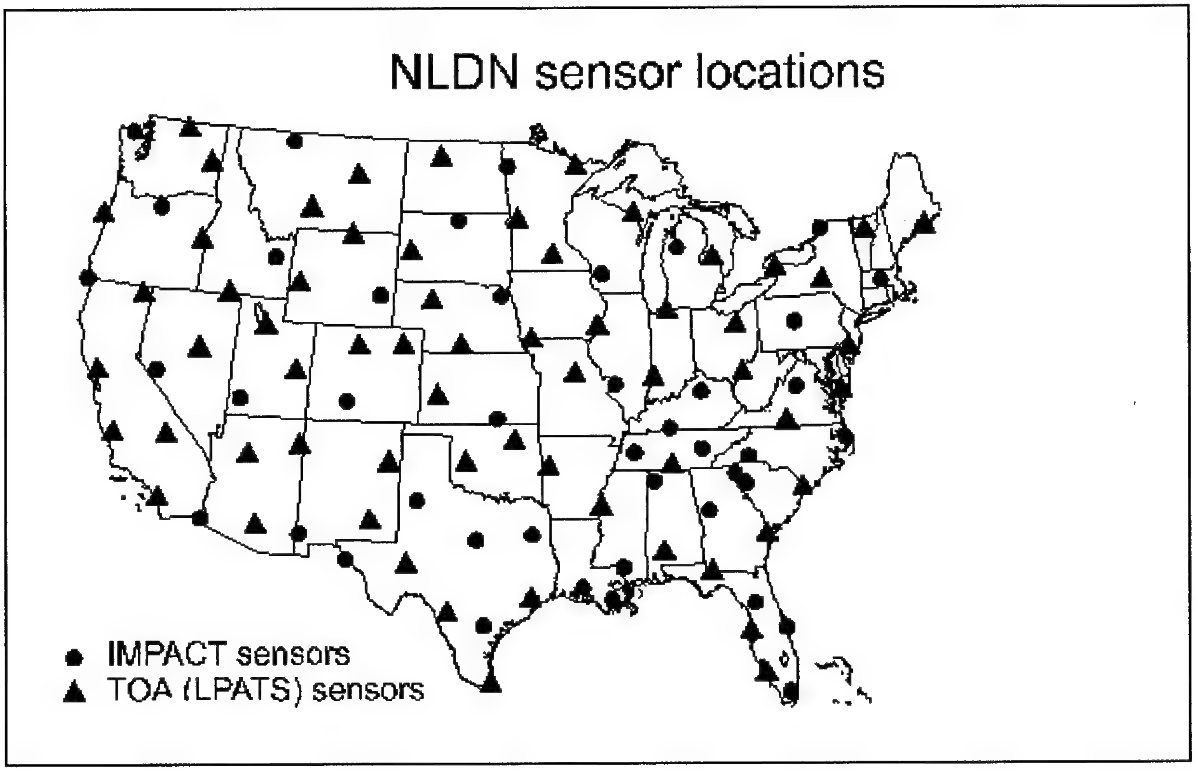

Figure 3. National Lightning Detection Network sensor locations. Triangles indicate IMPACT sensors, and circles indicate TOA sensors (Adapted from Cummins, et al., 1998)

In general, the 1994 upgrade improved location accuracy, percentage of lightning discharges detected, and long-term reliability of the NLDN. Cummins, et al. (1998) estimate the location accuracy of the NLDN increased to about 0.5 kilometer (km), where before the upgrade the location accuracy was only about 2.5 km. After the upgrade the detection efficiency was estimated to have improved from 65 – 80% to 80 – 90% for the first stroke with peak current of 5 kA or larger (Cummins, et al. 1998). An evaluation of the NLDN conducted by Idone, et al. (1998) over the Northeastern United States during and following the upgrade indicates modest increase in detection efficiency when compared to the network prior to the upgrade.

The NLDN records several pieces of information about each flash. The lightning data used in this thesis is flash information, where flash time and location, peak current, and polarity are from the first stroke in the flash only.

2.3 Methods of determining the distance cloud-to-ground lightning travels

This section will discuss and review current literature pertaining to two methods used to determine how far CG lightning travels. The particular methods reviewed are the Weather Surveillance Radar-88D (WSR-88D) storm centroid method and the Distance Between Successive Flashes (DBSF) method. Descriptions of both the storm centroid and DBSF method will be given, along with a discussion of the strengths and weaknesses of each method.

Two different methods have been developed to study how far lightning travels from storm center, lightning cluster center, or other lightning strikes. The first is the WSR-88D storm centroid method and the second is the DBSF method. Krider (1988) used the DBSF method to cluster CG lightning flashes for a study in Florida. López and Holle (1999) also did a study using the DBSF method for several areas. Renner (1998) used only the storm centroid method in his research, while Cox (1999) used both the storm centroid method and the DBSF method.

2.3.1 WSR-88D storm centroid method

The WSR-88D storm centroid method employs the two algorithms run by the WSR-88D Algorithm Testing and Display System (WATADS), which are then coupled with a program designed to place lightning data for the same time over WSR-88D images. The two algorithms are the National Severe Storms Laboratory (NSSL) Storm Cell Identification and Tracking (SCIT) algorithm, and the WSR-88D storm series algorithm. From the combined WATADS and lightning data, the horizontal distances between storm centroid and each lightning flash are calculated.

Prior to Renner (1998), little research had been conducted on the horizontal distance between storm cells and lightning flashes. Before the Build 9.0 version of WATADS, the radar algorithms could only identify entire storm systems, making it difficult to evaluate individual

storm cells. This made it nearly impossible to calculate the distance between cells and lightning flashes. Renner (1998) limited the scope of his research to two regions of four locations each. The initial region had predominantly air mass thunderstorms located in the Gulf Coast region and the second region had predominately synoptically driven thunderstorms located in the Southern Plains. He also limited the time frame of his study to April and July of 1996. Renner (1998) used the NSSL SCIT algorithm and the WSR-88D algorithm in Build 9.0 of WATADS to determine the location of storm centroids. The three output files from the two algorithms were combined to give a detailed list of storm centroid information. Next, he filtered the lightning data to exclude all flashes outside of a 60-nautical mile radius of each radar. An algorithm then combined the lightning and radar data and finally calculated distance between storm centroid and flash. Once calculations were made for the eight locations during April and July of 1996, a statistical analysis was conducted on the data.

Renner (1998) computed the frequency of cloud-to-ground flash distances for each of the sites for both months. From this study he concluded all regions have similar distributions, which show a significant number of lightning strikes from 2 to 6 nautical miles and a large drop-off of lightning flashes at distances greater than 16 nautical miles. He also found the mean and medians for all lightning flashes to be longer for April than July.

Renner (1998) then went on to compare several other categories. He compared percentages of lightning flashes to dBZ threshold, storm edge, the anvil region, the storm motion, and the maximum reflectivity above the zero degree Celsius line. Renner (1998) tried to compile operationally significant impacts and several rules of thumb from his analysis; however, the results were not very definitive. The cumulative distributions showed 75% of all lightning flashes were within 10 nautical miles for April, and 85% to 90% were within 10 nautical miles

for July. That study did not lead to strong conclusion about the adequacy of the 5-nautical mile safety radius criterion.

Cox (1999) posed the same question about the adequacy of the 5-nautical mile safety criterion as outlined in AFOSH 91-100 to provide adequate protection to life and property. Cox (1999) also limited the scope of his research to April and July of 1996. In addition, he narrowed his research to isolated air mass type thunderstorms with little vertical tilt and therefore chose five coastal locations in the southeastern United States. He used both the WSR-88D method and the DBSF method. This section will only discuss the WSR-88D method, while Section 3 will address the DBSF method.

Cox (1999) used the default parameters in Build 10.0 of WATADS to run both the WSR-88D storm centroid and the NSSL SCIT algorithms. These two algorithms generated three alphanumeric files, which contained all pertinent information on each storm centroid including latitude and longitude of storm centroid locations. Next, the algorithm sorted and combined lightning and radar data by time. From this file the shortest distance between flashes and centroids were calculated for each volume scan.

Cox (1999) noted the reliability of the WSR-88D method data was questionable. The same minimum distance occurs for all locations and times suggesting the occurrence is not natural. He hand tested a portion of the data, but he found no problems with the methodology. Assuming the results of the WSR-88D method are reasonable, Cox (1999) found the WSR-88D method appears to handle long-range lightning flashes better than the DBSF method. Using this method, Cox (1999) found 39% of the flashes for April and 32% of the flashes for July occurred at a distance greater than the lightning safety distance of 5 nautical miles.

Both Cox (1999) and Renner (1998) noted the time-consuming nature of using WATADS, as well as the enormous amounts of disk space required to process case studies, which limited the amount of data studied by either study. While comparing lightning and radar data would provide valuable information about lightning and storm variables correlation, this type of study would not be conducive to a large-scale climatological lightning study. The time consuming nature of WATADS limits the amount of data and number of cases an individual can tackle.

2.3.2 Distance Between Successive Flash (DBSF) method

The DBSF method provides another way of determining the distributions of CG lightning flash distances between individual flashes and lightning cluster centers. This method uses spatial and temporal methods to cluster lightning flashes into groups. Krider (1988) used a variation of this method to group lightning data for a study of three thunderstorms near Cape Canaveral, Florida. López and Holle (1999) used this method to conduct research on the distribution of distance between successive flashes for different types of storms in four different parts of the country. Cox (1999) also used this method in comparison with the WSR-88D method. A description of the method developed by López and Holle (1999) will be discussed along with a discussion of how Cox (1999) modified the DBSF method.

The method used by López and Holle (1999) works as follows. Using time-ordered data sets of lightning flashes from the NLDN database, an algorithm takes the earliest flash in the time series and selects a successive flash by picking the next flash in the ordered list not separated by 15 kilometers or 5 minutes. From the second flash, the algorithm finds the next successive flash by locating the next flash in the time-ordered list not separated by 15 kilometers or 5 minutes. A series of consecutive flashes constitutes a cluster of flashes as long as all happened within the spatial and temporal constraints. Termination of the search happens when

the next flash in the time-ordered set occurs more than 5 minutes after the last flash assigned to a cluster. If a particular flash does not meet the time and distance criteria it is tagged as an outlier, and the algorithm goes to the next flash in the ordered data. Outliers are identified as candidates for other clusters. The algorithm runs on the time-ordered list of unused flashes and will start with a previously identified outlier for the next cluster. The method continues until each flash has been assigned to a cluster or is designated as isolated flash. An isolated flash is defined if no other flash meets the time or distance criteria required to pair flashes.

Cox (1999) used the DBSF method also but with some modifications for his research. Cox (1999) ensured only the lightning data correlated with storm centroids would be used in the DBSF algorithm. The algorithm used by Cox (1999) has a 6-minute time criterion, which corresponds to a volume scan length, but used the same spatial criterion of 15 kilometers. The algorithm calculates successive flashes from the time-ordered data set; however, a fixed time increment of 6 minutes was used. This means the time length of any cluster can only be 6 minutes long. Eventually the algorithm assigns all lightning flashes to a cluster or identifies them as isolated flashes. The isolated flashes in the already pared down data set constituted 30% of the flashes. These isolated flashes were thrown out of the analysis. All flashes in a cluster were averaged together to determine a lightning centroid, and then the distance from each clustered flash to the lightning centroid was calculated. Note this distance is different than the distance between each successive flash calculated by López and Holle (1999).

Krider (1988) studied both the distributions of the nearest neighbor distances between CG lightning strike points and distributions of successive flashes. Krider (1988) found 1 – 4 km to be the most probable distance between successive flashes with an average distance of 3 – 4 km. López and Holle (1999) suggest modifying current lightning safety education, from 2 – 3 miles

from a previous strike to 6 – 8 miles to ensure adequate personal safety. Renner (1998) found the average distances for all stations in his study were from 4 – 8 nautical mile. Cox (1999) found that about 30% of lightning flashes occur beyond the 5-nautical mile safety radius. All of these findings suggest the current Air Force criterion of 5-nautical miles might not be adequate to protect life and property.

3. Methodology

3.1. Objectives

The primary goal of this research was to study the spatial and temporal patterns of CG lightning in an effort to determine the horizontal distance between lightning flashes and cluster center, or between an isolated flash and its nearest flash. From this information the 5-nautical mile lightning standoff criterion outlined in AFOSH 91-100 could be investigated and the adequacy of a single "safe" distance determined.

The initial step was to devise a method of grouping lightning flashes into clusters, which would not only handle large amounts of data, but also reduce the number of isolated flashes present in earlier studies. The next step was to study both the distance distributions of each clustered flash to the cluster center, and the distances of the isolated flashes to its nearest-neighboring flash. The cluster center is the arithmetic average of all the lightning flash positions in a lightning cluster. The term lightning cluster refers to a group of lightning flashes grouped together. The final goal of this research was to expand the study to encompass the entire continental United States for March through November from 1995 to 1999. This will give a comprehensive climatological type study of lightning activity over the continental United States.

3.2 Scope

Preliminary investigations into the topic revealed two methods, which could be used to determine the horizontal distance CG lightning travels. First, the WSR-88D storm centroid method employed by Cox (1999) requires copious amounts of time and computer memory. Processing Level II data from the WSR-88D with current tape drives requires a considerable amounts of time, limiting the number of cases and amount of data which could be studied. WSR-88D data poses another problem since lightning distance distribution can only be studied

in close proximity to radar sites, again limiting the amount of lightning data and locations studied.

The second method involves using only lightning data. The distance between successive flash groups flash positions of CG lightning using spatial and temporal criteria. This method required large amounts of computer memory for output, but an enormous amount of data can be analyzed in a relatively short amount of time. For these reasons the distance between successive flash clustering method was chosen for this research.

The NLDN was upgraded in 1994, and therefore only lightning occurring after the upgrade was included in this research project so as to maintain consistency of the data set. The data from the NLDN covers the entire continental United States and were readily available. After the upgrade, the detection efficiency improved from 65 – 80% to 80 – 90% for first strokes with peak currents of 5 kA or larger (Cummins et al. 1998). The location accuracy of the NLDN is now at about 0.5km, whereas before the upgrade the location accuracy was only about 2.5 km. Because of this increased detection efficiency and location accuracy, only post-upgrade lightning data is used in this research.

Orville and Huffines (1999) show typical flash counts for months March though November as having the most lightning, and the months December, January, and February as having the least amount of CG lightning, over the entire United States. Therefore, it seems reasonable to use lightning data from the months of March through November for each of the years 1995 through 1999. October and November 1999 being the exception and were not included in the data set because these months were not available at the time of data processing. Using only those months, data was broken down further into seasons where March through May

constitute spring, June though August constitute summer, and September through November constitute fall.

Next, choosing the location for this research was important. Previous studies were limited to the either the Gulf Coast, Florida, or Colorado. This research examines the entire continental United States, however to improve data handling six regions were selected. Figure 4 shows the breakdown of the United States into the six regions and Table 1 lists each region with descriptive latitude and longitude.

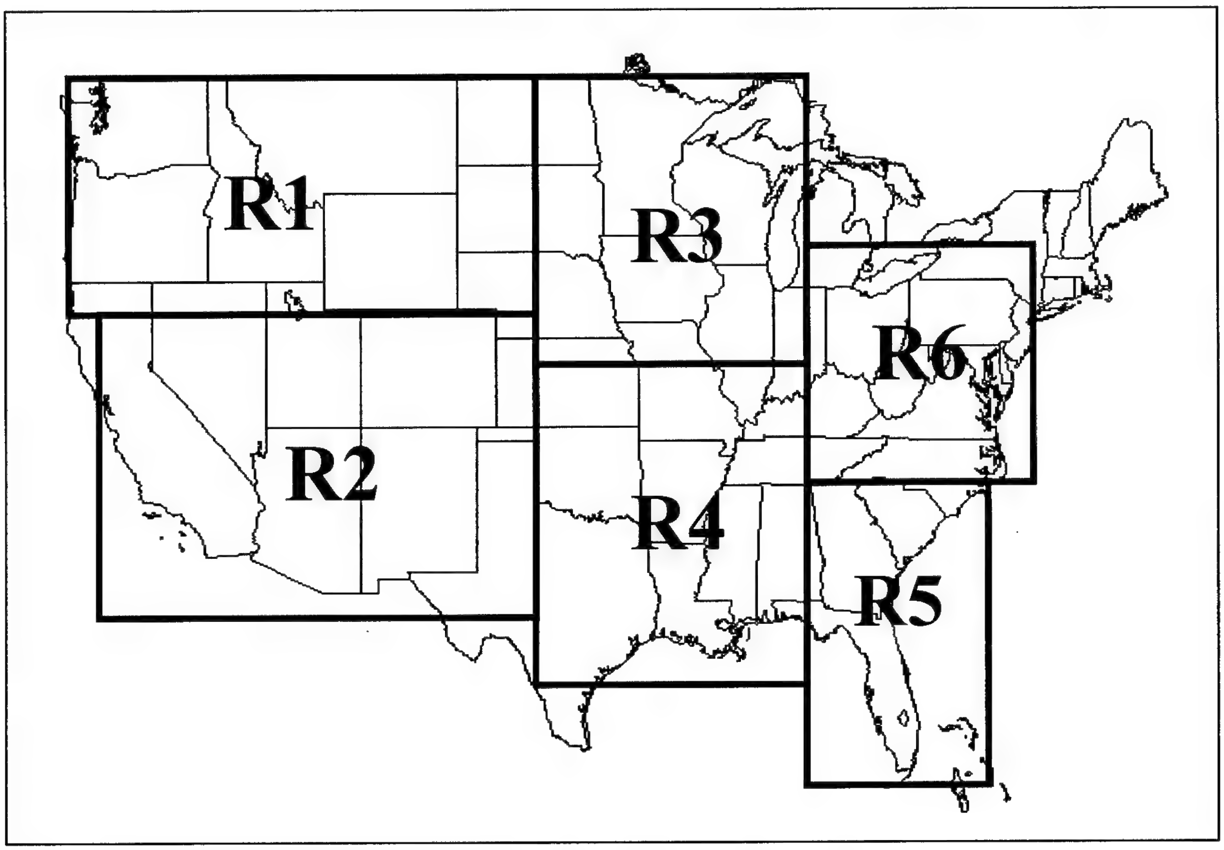

Figure 4. Regional breakdown of the continental United States. This was used when processing lightning data and for describing data results.

Where previous work investigated only very short time frames and limited locations or number of thunderstorms studied, this research explores nearly the entire continental United States from March to November for virtually 5 years. The idea was to study as much lightning data as possible in the hope that flash positions of CG lightning would reveal patterns or lead to insights about what constitutes safe distances. Since location was not limited and the time of the year was only narrowed to spring, summer, and fall months, a variety of thunderstorm types such as multicelluar storms, supercell storms, squall line storms, and mesoscale convective storms would all be included in this study. Because of the wide scope for location and time, this research leads to a climatological type study of lightning distance distributions across the United States.

Table 1. Regions with associated latitude and longitude ranges.

Location	Latitude range	Longitude range
Region 1	41.0 to 49.0 North	102.0 to 126.0 West
Region 2	31.0 to 41.0 North	102.0 to 125.0 West
Region 3	37.0 to 49.0 North	88.0 to 102.0 West
Region 4	28.0 to 37.0 North	88.0 to 102.0 West
Region 5	25.0 to 35.0 North	77.0 to 88.0 West
Region 6	35.0 to 35.0 North	75.0 to 88.0 West

3.3 Data

This research used lightning data collected by the NLDN, which has been quality controlled and archived. The NLDN records cloud-to-ground flashes across the continental United States from 106 sensors as shown in Figure 3 and described in Section 2. The lightning data used in this thesis is flash information and includes month, day, year, hour, minute, second, latitude, longitude, peak current, and multiplicity. The time, location, and peak current are taken from the first stroke detected in each flash.

3.4 Clustering method

The basic methodology used by López and Holle (1999) and Cox (1999) to group flashes into clusters has been adapted for this study. Different spatial and temporal criteria were studied to find an optimum time and distance constraints, which would lower the isolated flash rate to an acceptable level. The clustering method with the new time and distance constraints was used to initially group all flashes. After the initial grouping of lightning flashes into clusters, another algorithm took the single flashes or isolated clusters and associated many of them with nearby clusters. This was only done when the isolated flash met certain time and distance criteria to the next closest flash. Final output files for each flash and each cluster were created and then analyzed.

A general description of the clustering process is given here, and a specific example of the clustering method is given in Section 3.4.3. All algorithms were written in the Interactive Data Language (IDL), a programming language by Research Systems Inc. located in Boulder, Colorado. The process starts when an algorithm generates a file containing dates, time, region and file tag name for each day of March through November from 1995-99 for a given region. The time for each day goes from 0500 UTC to 0500 UTC. Dividing the days at 0500 UTC was

done so the change from one file to the next would happen in the middle of the night, and hopefully limit the amount of lightning due to convective systems. Synoptic type systems are not dependent on daytime heating and the choice of time would not limit the amount of lightning occurring. The dates are then fed into run_batch program, which in turn reads in one day at a time and processes all the lightning data from that day in a particular region as described below.

The lightning data for a day was extracted from the archives in binary format and then converted to an ASCII format. If the number of flashes for the day were more than 1000 then the program continues; if not then this day was skipped. If a region in Figure 4 has less than 1000 flashes, this would indicate very little lightning activity during a particular day, excluding these days seemed reasonable. So for days with more than 1000 flashes in the specified region, the lightning flash data were sent to an initial clustering program, and two output files were generated. The initial file was called a **flash** file and contained date, time, assigned cluster number, latitude, longitude, peak current, and multiplicity of each flash. The second file generated was a **stat** file and contained date, time, cluster number, count, average latitude of cluster, average longitude of cluster, maximum positive peak current, maximum negative peak current, and standard deviation of flashes in each cluster. The date and time belong to for the earliest flash in the cluster, count refers to the number of flashes assigned to the cluster, and the cluster center was defined as the arithmetic mean of the latitude and longitude of all flash positions in the cluster. An example of each of these files can be found in Appendix A.

Next, the **stat** and **flash** files were fed into an algorithm, which associates the isolated flash with the cluster of the nearest flash to that isolated flash. Isolated flashes cloud be associated with clusters of flashes or with other isolated flashes. Two output files were generated. The **iso** file contains the date, time, latitude, longitude, and peak current of the

isolated flash, followed by the distance to the nearest neighboring flash, and finally the date, time, latitude, longitude, and cluster number of the nearest flash. The second output file was the **fnew** file, which contains the date, time, newly assigned cluster number, latitude, longitude, peak current, and multiplicity of each flash. An example of these two files can be found in Appendix A.

Finally, the **fnew** file of all flashes, including newly assigned isolated flashes, was fed into an algorithm, which calculates the new information about the clusters. The output generated was a **snew** file and includes date, time, cluster number, count, average latitude of cluster, average longitude of cluster, maximum positive peak current, maximum negative peak current, and standard deviation. Again, the date and time refer to the earliest flash assigned to the cluster, the count was the total number of flashes assigned to the cluster, and the average latitude and longitude were the lightning cluster center. The final output was the **f** file, which consists of all the same information as the **fnew** file for all individual flashes, with the addition of the distance each flash was from it's cluster center. Note that "zero" distance in this method amounts to an isolated or single flash cluster. Examples of these two files are located in Appendix A.

3.4.1 Optimizing time and distance criteria

The clustering method used by Cox (1999) used a time constraint of 6 minutes and a distance constraint of 15 km. Cox (1999) ended up with a large percentage of isolated flashes, which he discarded. The idea was to choose a time and distance combination that seemed reasonable in length, but would also reduce the number of isolated flashes. The percentage of isolated flashes comes from summing up the number of isolated flashes and dividing by the total number of flashes. Reducing isolated flashes was done by determining the optimum time and distance intervals for the flash grouping algorithm. Test data from 5 different locations at 10,000

flashes each was taken and grouped according to the clustering algorithm, with different combinations of time and distance, then a comparison of distance and time combinations was examined. From these different combinations a delta distance of 17 km and delta time of 12 minutes lowered the percentages of isolated flashes to less than 30% for all test cases.

3.4.2 Associating isolated flashes to clusters

After optimizing the time (12 minutes) and distance (17 km) criteria in the initial clustering algorithm, between 18% and 30% of the flashes were still isolated flashes or single flash clusters in the 5 test cases. This was less than the combination of 15 km and 5 minutes, but still too many flashes to be discarded, so an attempt was made to associate as many of these isolated flashes with clusters as possible. To begin associating isolated flashes, all isolated flashes were found, then all flashes within plus or minus 15 minutes of an isolated flash were gathered. Finally the nearest flash to the isolated flash was found. If at this point the nearest flash was equal to or less than 17 km from the isolated flash, the isolated flash was assigned to the cluster of its nearest neighbor. If the nearest neighbor to the isolated flash in the time window was not within 17 km, then the isolated flash remained an isolated flash.

3.4.3 Clustering method example

For this example the reader should refer to Figure 5 as a visual aid to the description that follows describing how flashes are grouped into clusters. The clustering method starts by obtaining time-ordered sets of lightning flash data from the NLDN database. The numbers in the diagram indicate the time sequence of each flash. Flash 1 in Figure 5 is the earliest flash in the time-ordered data and is assigned as the first flash of cluster 1. Then all flashes occurring within the time criterion of 12 minutes of flash 1 are collected. The algorithm takes the first flash in the time series and selects a successive flash by picking the next flash in the ordered list not

separated by more than the distance criterion of 17 km. In this way flash 2 becomes the second flash in the cluster. From this second flash, the algorithm finds the next successive flash by locating the subsequent flash in the time-ordered list not separated from this flash by more than 17 km, and adds this successive flash to the cluster. In the same way flashes 3, 4, and 5 are added to the cluster. However, flashes 6, 7, and 8 are at distances greater than 17 km from flash 5. These flashes are tagged as candidates for other clusters and the algorithm goes to flash 9 which meets the distance criterion from flash 5, so flash 9 becomes the next successive flash in the cluster. Flashes 12, 13, and 14 are added in the same way to cluster 1.

Termination of the search for successive flashes takes place when one of two events occurs. The search stops when a flash in the time-ordered data exceeds the time criterion of 12 minutes from the earliest flash in the cluster. The search also terminates when no more flashes meet the distance criterion from the last flash added to the cluster.

The next cluster starts with the first unused flash in the time-ordered data. In this example, the initial flash in cluster 2 would be flash 6 in Figure 5. In the search for flashes to cluster, only flashes not used in previous clusters and within 12 minutes of the flash 6 are considered for the new cluster. The algorithm searches for the next flash by the same method described above.

Initially all remaining flashes become grouped except flash 15 and flash 18. Flash 15 does not meet the distance criterion to flash 14 in cluster 1 or flash 11 in cluster 2, so flash 15 initially becomes a single flash cluster. Flash 18 does not meet the distance criterion to flash 14 in cluster 1 or flash 17 in cluster 2, so flash 18 also becomes a single flash cluster.

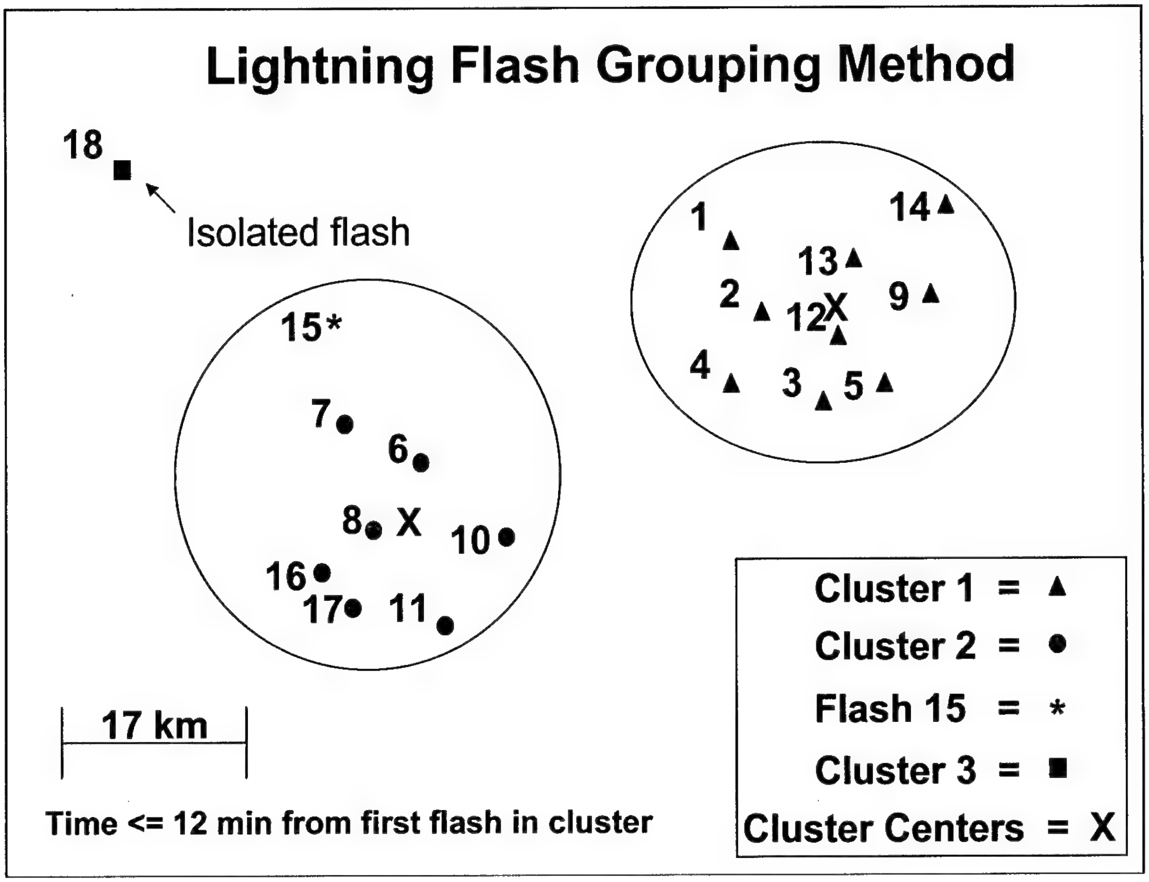

Figure 5. Schematic of the grouping lightning flashes into clusters. The numbers indicate the time sequence of each flash.

At this point flash 15 and flash 18 are isolated flashes. The distance between the center of the single flash cluster and that flash will be a zero distance. To avoid having a large number of single flash clusters, these isolated flashes become part of the nearest cluster, so long as they meet time and distance criteria to at least one flash in the nearby cluster. To incorporate as many isolated flashes as possible into clusters, a longer time interval was chosen when selecting flashes to compare to the isolated flash. Expanding the time interval around the isolated flash to plus or minus 15 minutes would allow for flashes at the edges or just a little to late to be included into nearby clusters. Essentially this just expands the search for flashes to be grouped together. For each single flash cluster, all flashes within plus or minus 15 minutes are collected, and the

nearest neighbor is found. If the isolated flash and its nearest neighbor are within 17 km, the single flash cluster is assigned to the cluster of the nearest neighboring flash. Flash 15 is within 17 km of flash 7. If no flashes are within plus or minus 15 minutes or no flashes within 17 km of the single flash, then the flash becomes an isolated flash. Flash 18 is an isolated flash in this example because no other flashes are within 17 km.

The next step is to calculate the new center of each cluster by finding the average latitude and longitude of all flashes in a cluster. From the center point of the clusters, distances are calculated to each flash in each cluster and stored in the **f** file, so distance distributions can then be analyzed. The distances of the isolated flashes from their nearest neighbor is also calculated and stored.

3.4.4 Data analysis methodology

To analyze the flash information an algorithm was created to combine all **f** or **stat** files for a particular region by month or season. Another algorithm calculated the mean, median, standard deviation, and variance of all flashes or clusters in a set of combined data. A third algorithm calculated these same properties for the remaining isolated flashes from a combined data set. Next, from the combined flash data for months or seasons, an algorithm calculates a frequency distributions and cumulative frequency distribution of the clustered or isolated flashes in each bin. Each bin represents a range of distances and the frequency distribution displays the number of flashes in each bin. Also, the distances for clustered flashes is the distance between each flash and associated cluster center, while the distance for the isolated flashes is the distance between the isolated flash and it's nearest neighbor. The histogram routine in IDL counts the number of flashes occurring in each bin. The bins in these calculations go from equal to or greater than 0.0 to less than 1.0 km for bin 1, then from equal to or greater than 1.0 to less than

2.0 km for bin 2, and so on. These number of flashes in each bin were sent to an output file, and then manipulated in Microsoft Excel until graphs of the histograms and cumulative frequency distributions were created. This procedure was carried out for each region and each season or month for both clustered and isolated flashes.

Finally, flash densities for both the clustered flashes and isolated flashes were calculated by taking the total number of flashes in each bin for all 9 months in each region and then dividing by the area of a circle with the radius of the bin distance. Figure 6 shows an example of how the flash density area can be visualized. This method of calculating flash density assumes flashes are isotropically distributed inside the circle.

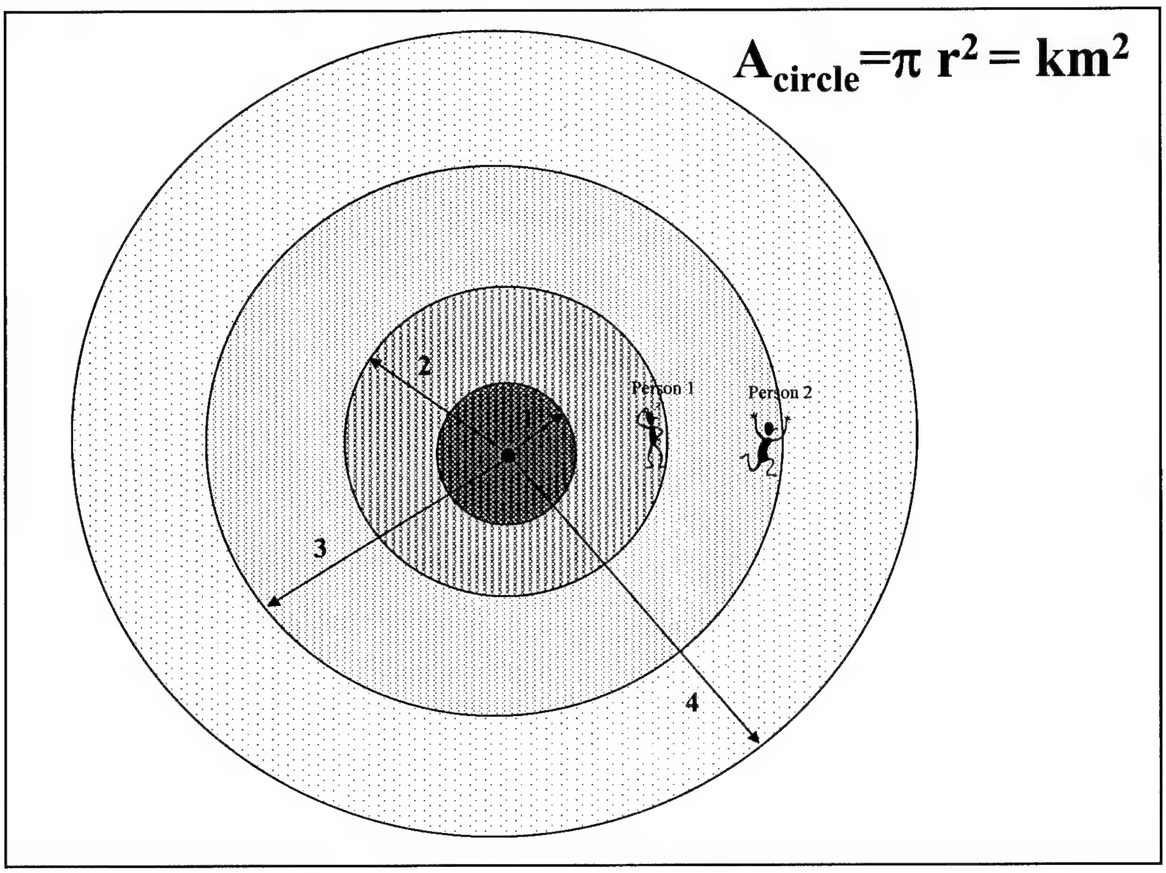

Figure 6. Circular area used for describing flash density. Each circular bin around the cluster center or isolated flash was used to calculate the area when finding flash densities. Flash densities are the number of flashes per sq km of each circle with radius r, where r equals 1 –4 km in this diagram.

Taking the total number of flashes and dividing by area gives the probability of a lightning strike in a circular area around some point. The point can either be the isolated flash or the cluster center. The data is then normalized by region so each region has a normalized plot of flash densities. Normalization by region takes into account the difference in total number of flashes by region.

The probability per unit area refers to the possibility of lightning striking a particular position in a circle around some point, and is different from the probability of lightning striking at a particular distance from some point. The distinction between the straight cumulative frequency distribution and the one weighted by area is worth noting. The cumulative frequency distribution shows the probability of a lightning flash striking at a particular distance, while the normalized graphs show probability of a lightning flash striking a particular position in a given area.

4. Results and Analysis

4.1 Management of isolated flashes

An isolated flash is defined as a flash that did not get paired with any other flash or cluster of flashes. Therefore, an isolated flash amounts to single flash cluster. The percentage of isolated flashes was defined as the number of isolated flashes divided by the total number of clusters. This is the same way Cox (1999) defined the percentage of isolated flashes. Even after the initial clustering algorithm was run with a distance constraint of 17 km and a time constraint of 12 minutes, as many as 18% to 37% of the clusters were still single flash clusters. It would do no good to discard the single flash clusters as was done in previous research projects, because it is precisely the isolated flashes which prove most dangerous. Dealing with these isolated flashes and either associating them with clusters or scrutinizing them individually was a large part of this research effort. Since isolated flashes as outliers can be dangerous, it seemed important to consider and study the distribution of these isolated flashes. In this section, the terms isolated flash and single flash cluster will be used interchangeably.

The clustering algorithm investigated each isolated flash in relationship to all other flashes within plus or minus 15 minutes of itself, and spatially found the nearest neighbor. The isolated flashes were assigned to the cluster of the nearest neighbor if this neighboring flash was within 17 km and within plus or minus 15 minutes of the isolated flash. Tables 2 and 3 provide a comparison of the percentages of isolated flashes before and after the assignment of additional isolated flashes to clusters.

Table 2. Percentage of clusters that are isolated flashes before assigning isolated assigned to clusters. Figure 4 shows the different regions.

Region	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
1	37%	35%	32%	28%	25%	25%	28%	33%	36%
2	32%	31%	27%	23%	21%	21%	23%	25%	27%
3	28%	27%	24%	22%	22%	22%	23%	27%	30%
4	24%	22%	20%	20%	20%	21%	23%	24%	25%
5	26%	25%	22%	24%	23%	25%	28%	30%	29%
6	27%	25%	21%	18%	19%	20%	22%	26%	27%

Table 3. Percentage of clusters that are isolated flashes after assignment of isolated flashes to clusters. Figure 4 shows the different regions.

Region	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
1	29%	26%	24%	19%	17%	17%	20%	26%	29%
2	26%	26%	20%	16%	14%	14%	15%	17%	23%
3	18%	17%	15%	14%	13%	14%	15%	18%	21%
4	11%	10%	9%	10%	11%	11%	13%	12%	13%
5	17%	16%	14%	16%	16%	17%	20%	22%	21%
6	17%	15%	12%	11%	12%	13%	14%	18%	18%

The percentage levels of single flash clusters dropped after assignment of some single flash clusters to other clusters. However, 9% to 29% of the clusters were still single flash clusters, which is still too many clusters to be ignored. Table 4 shows the percentages of single flash clusters flashes before and after by season for each of the six regions (Figure 4). Decreases of 6 – 11 % in isolated flashes occur seasonally once some of the isolated flashes were added to clusters. However, with single flash clusters still at 10% to 26% seasonally, isolated flashes needed to be studied to determine characteristics of these flashes.

Table 4. Percentages of isolated flashes before and after assignment of isolated flashes by region.

	Spring		Summer		Fall	
Region	Before	After	Before	After	Before	After
1	33%	26%	26%	18%	29%	18%
2	28%	22%	21%	10%	23%	12%
3	25%	16%	22%	14%	25%	17%
4	22%	10%	21%	11%	24%	13%
5	25%	16%	24%	16%	29%	21%
6	23%	14%	19%	12%	24%	16%

The distance distributions within the clusters and the distance distributions of the isolated flashes to their nearest neighbor will be studied. Note these two distances are different. The cluster distances are a measure of the distance from each flash in the cluster to the cluster center. The isolated flash distances are a measure of the distance from the isolated flash to the next nearest flash within plus or minus 15 minutes of the isolated flash.

The magnitude of the number of isolated flashes needs to be placed in perspective. Table 5 shows the number of isolated flashes divided by the total number of flashes seasonally. Isolated flashes can be thought of in two ways. First, an isolated flash is just a single flash cluster, and second, the isolated flash is one of the total numbers of flashes in this study. Isolated flashes make up a smaller percentage of the total number of flashes than the total number of clusters.

Table 5. Percentage of isolated flashes out of the total number of flashes by region.

Region	Spring	Summer	Fall
1	7.4%	3.8%	5.8%
2	6.1%	2.7%	3.9%
3	3.6%	2.0%	3.6%
4	2.3%	1.6%	2.8%
5	2.9%	2.0%	3.8%
6	2.7 %	1.0%	9.0%

4.2 Characteristics of clustered lightning flashes

When clustering the flashes, there was no way of knowing if flashes grouped together were from the same thunderstorm or charge regions. The method uses patterns from flash positions and bases flash grouping solely on spatial and temporal conditions. For this reason nothing can be inferred about the relationship between lightning distributions and thunderstorm types or thunderstorm parameters.

The results presented in this section refer to the characteristics of clustered lightning flashes and the distances between each clustered flash and the cluster center. An understanding of the clustered lightning flashes must be gained before delving into the characteristics of isolated flashes and how far they are from the clusters. The cluster center was defined as the arithmetic average of the latitude and longitude of all flashes in the cluster. From each cluster center point the distance to each flash in the cluster was calculated and stored. All flash information for an entire month or season was assembled, and the mean distance from cluster center to each clustered flash was calculated. The median distance, standard deviation, and variance of these distances were also calculated. Because an IDL program was used to tally the number of distances which fall into each bin of the histogram, the percentile for the 9.26 km (5 nautical miles) could not be calculated exactly. Since the bin for 9 km extends from equal to or greater than 9.0 km to less than 10.0 km, and 9.26 km falls within this bin, it is sufficient to look at the percentile at which the 9-km bin occurs. Knowing the percentile at the 9-km bin helps assess the adequacy of the 5-nautical mile Air Force safety rule.

For the matter of simplicity, all information will be displayed for Region 5 only. Region 5 was chosen to display all results and graphs because this region has the most lightning flashes

of all the regions. Tables displaying summary information and graphs for all other regions are located in Appendix B.

Tables 6 and 7 display the summary information for Region 5. The data for each of months presented in Table 6 corresponds to all data in each month for the years 1995-99, and the data in Table 7 represents all data in Region 5 for each season from 1995-99 also. The clustered flashes in Region 5 show mean distances of flashes from cluster center to be between 6.51 km to 8.41 km, with median distances ranging from 5.03 km to 6.90 km. Each median is slightly smaller than the each mean. The median distances tend to be shorter than the mean distances due to the asymmetric nature of the distributions. Median values tend to be insensitive to a number of extreme values, while the mean values tend to be greatly influenced by extreme values.

Table 6. Region 5 clustered flash summary statistics by months. Number of flashes, mean distance to cluster center, median distance, standard deviation, variance, and percentile at 9-km bin. Note October and November do not include 1999 data.

Region 5	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Mean (km)	8.41	8.37	8.06	7.21	7.35	7.00	6.51	7.02	7.08
Median (km)	6.90	6.81	6.40	5.60	5.63	5.30	5.03	5.63	5.81
Std Dev (km)	6.46	6.49	6.43	5.92	6.14	5.49	5.44	5.68	5.50
Variance (km^2)	41.78	42.07	41.38	35.06	37.74	35.43	29.58	32.22	30.24
Percentile at 9-km bin %	68.0	68.5	70.2	75.3	74.0	76.0	78.8	75.8	75.9

Table 7. Region 5 clustered flash summary statistics by seasons. Number of flashes, mean distance from cluster center, median distance, standard deviation, variance, and percentile at 9.26 km. Note October and November do not include 1999 data.

Region 5	Spring	Summer	Fall
Number Flashes	5,100,043	16,183,469	2,754,808
Mean (km)	8.23	7.20	6.66
Median (km)	6.64	5.51	5.20
Std Deviation (km)	6.46	6.03	5.49
Variance (km^2)	41.71	36.30	30.18
Percentile at 9-km Bin %	69.1	74.9	70.3

The standard deviation and variance measure the variability or dispersion of the flashes in the cluster. The standard deviations are all within 1 km of each other and show little variation in the distribution over different months or seasons for Region 5. This can also be seen in Table 6. The spring months have the most variations of flashes around the cluster center, and the fall has the least.

The next figures display graphical presentations of the frequency distribution of number of flashes per kilometer, and cumulative frequency distributions for each of the seasons. Only graphs for each season for Region 5 are included here. The percentage of flashes in the clusters greater than 5 nautical miles (9.26 km) is marked on each cumulative frequency distribution with a solid line. These lines are meant to be crude representations of the actual numbers listed in the table and are for visualization only.

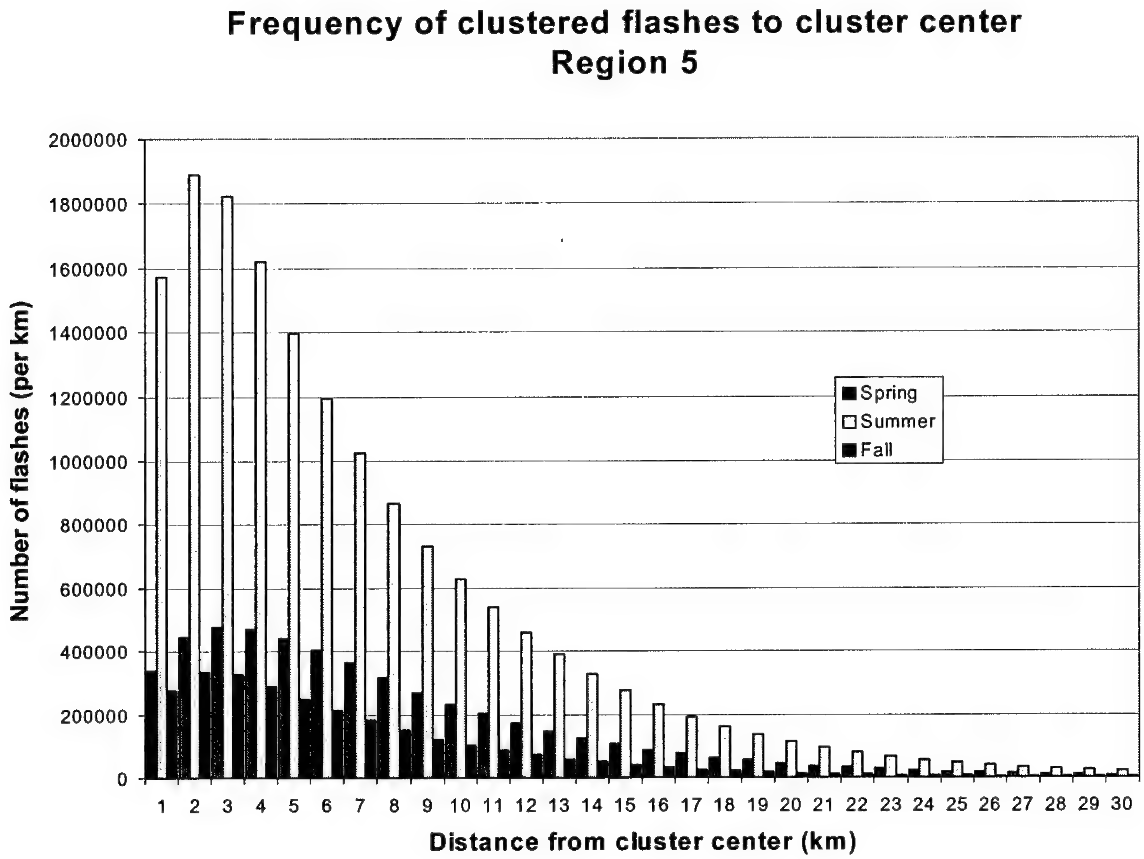

Figure 7. Region 5 frequency distributions of flashes per km from cluster center. Frequencies for Spring, Summer, and Fall.

The frequency distribution in Figure 6 reveals the greatest number of flashes occur in the summer in Region 5, as is expected. The least frequent number of flashes happen in the fall months, while the spring frequency is slightly higher than that of the fall. Each frequency distribution has approximately the same shape and all are positively skewed.

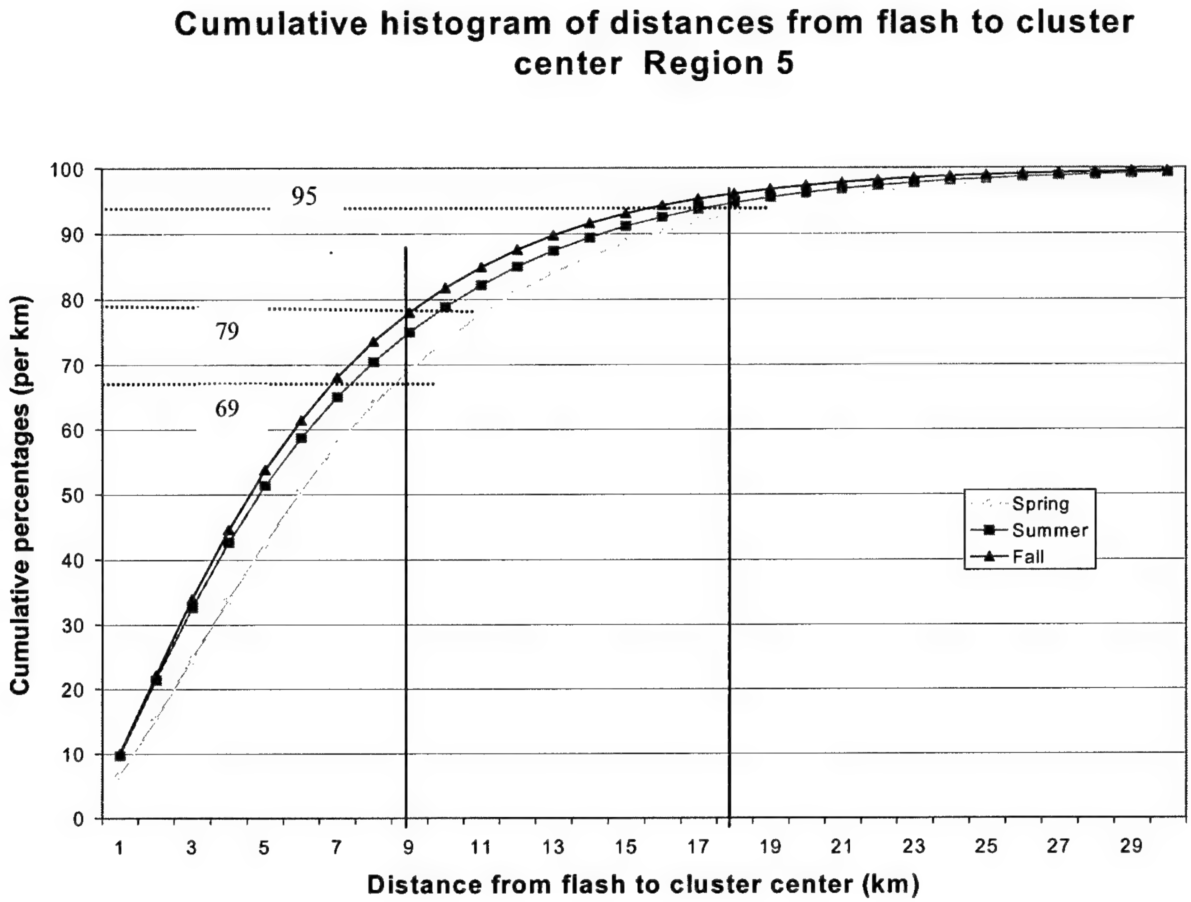

Figure 8. Region 5 cumulative frequency distribution of clustered flashes per km from cluster center. Spring, Summer, and Fall.

Figure 7 provides a graphical representation of the cumulative frequency distribution for each of the seasons in Region 5. From this diagram, percentages of flashes from the cluster centers can be determined. At the 9 km bin, between 69% in the spring and 79% in the fall of the flashes are within 10 km of the cluster center. This leaves 31% to 21% of the flashes striking beyond 10 km from the cluster center. Note that 5 nautical miles equals 9.26 km and that this distance falls in the 9 km bin in the graph. This historical lightning data can be used to determine what is a safe distance. If the safety criteria state you need to be 95% sure you won't be in danger of lightning striking and you are in Region 5 during the summer, you would need to

be 20 km from the center of lightning cluster. Again, similar summary information is located in Appendix B for each of the other regions.

4.3 Characteristics of isolated lightning flashes

Like the clustered flashes, there was no way of knowing if the isolated flashes studied here were actually from a particular thunderstorm, or if the isolated flash really belonged with a group of flashes. The isolated flashes were defined strictly by not meeting spatial and temporal conditions to other flashes, therefore nothing can be inferred about these flashes in relationship to thunderstorm parameters. One can only speculate that these isolated flashes come from a convective cloud away from the main system or from a highly charged thunderstorm debris cloud, or that the flash comes from the anvil at great distances from the main thunderstorm.

The results presented in this section refer to the characteristics of only the isolated flashes. The distances in this section refer only to the distance between the isolated flash and its nearest neighboring flash within plus or minus 15 minutes of the isolated flash. Again for simplicity, only information for Region 5 will be presented in this section; however the same table and graphs for Regions 1, 2, 3, 4, and 6 are located in Appendix C.

The data for each of month presented in Table 8 corresponds to all data in each month for the years 1995-99. Exceptions to this are for October and November, which only go from 1995-98. For the isolated data, seasonal information was not calculated and information was only available by month. However, representative months for each season have been selected, and the frequency distribution and the cumulative percentages of isolated flashes are displayed.

The information presented in Table 8 is for Region 5 by month. All information for an entire month was gathered and a mean distance from an isolated flash to its nearest neighbor was calculated. The median, standard deviation, and variance of these distances were also calculated.

The distances and variances for the isolated flashes are all larger than those for the clustered flashes. The isolated flashes are "lone" flashes and could not be paired with other flashes. It would be tempting to discard these flashes from the data set, and concentrate solely on clustered lightning flashes, but the isolated flashes do strike the ground and could prove to be the most dangerous, as people are generally not expecting a single lightning flash.

Table 8. Region 5 isolated flash summary statistics by months. Mean distance to the nearest flash, median distance, standard deviation, variance, and 90th percentile. Note October and November do not include 1999 data.

Region 5	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Number of isolated flashes	48798	48435	48895	90253	120929	112425	65392	24912	15617
Mean (km)	38.79	30.07	30.10	30.17	27.60	35.81	51.71	99.90	39.72
Median (km)	19.64	18.93	20.47	19.51	18.68	21.46	23.08	28.15	19.92
Std Dev (km)	79.93	46.27	43.59	43.97	37.13	46.65	83.17	178.75	71.52
Variance (km^2)	6388	2140	1900	1933	1378	2176	6917	31950	5115
90 th Percentile (km)	41	42	46	49	50	51	54	54	50

The mean distances to the nearest neighboring flash range from 27.6 km in July to 99.9 km in October, with the summer three months having the lowest means and the fall having the highest mean distances. Median distances for the spring and summer are similar, but are larger for the fall months. Median distances range from 18.68 km in July to 28.15 km in October. The median distances are all smaller than the mean distances. The isolated flashes at great distances will increase the mean distances because outliers weigh into the mean value. While, the median

distances will not be affected by isolated flashes at great distances and therefore, may be a better representation of the average distance isolated flashes are from the nearest neighboring flash.

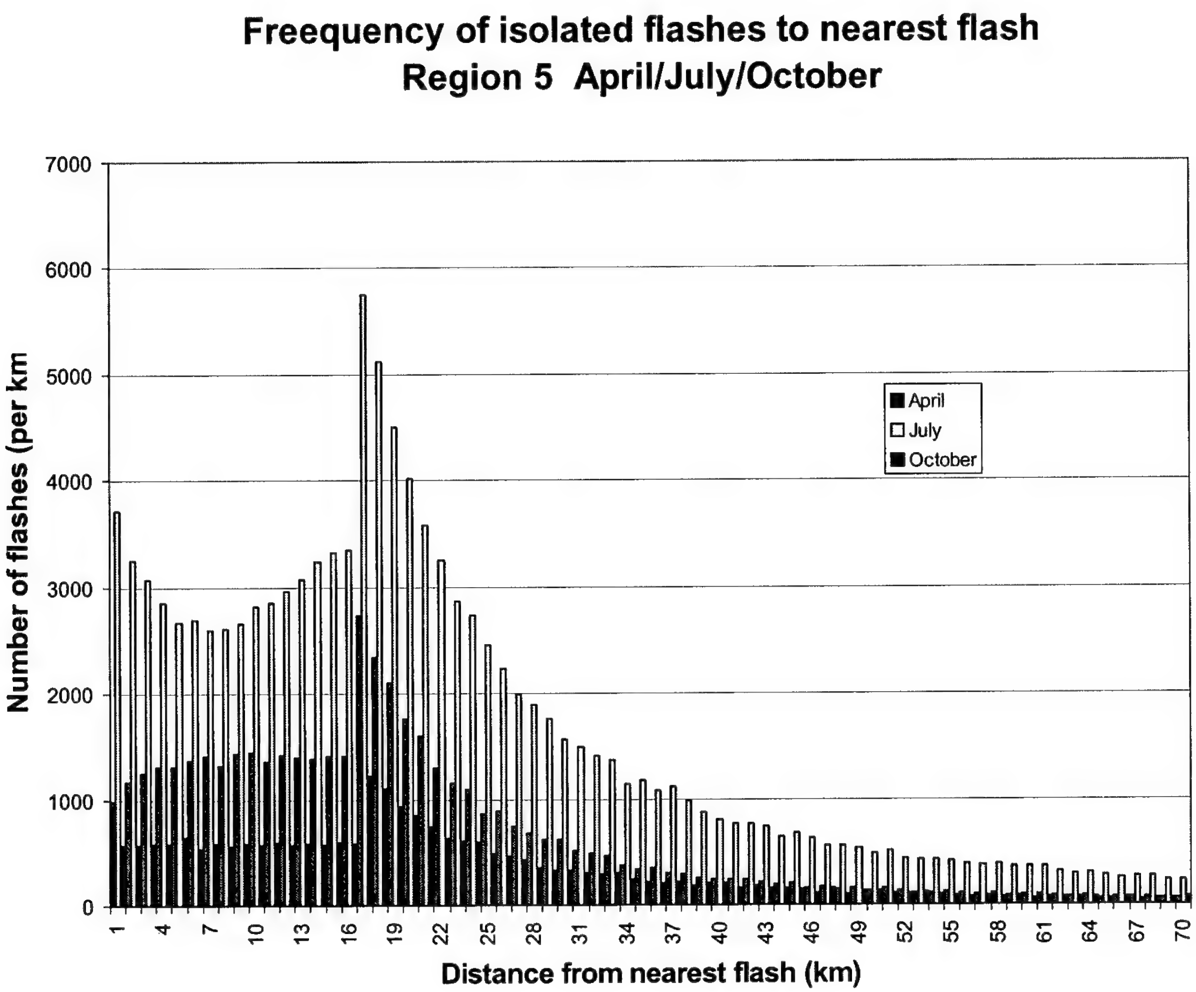

Figure 9. Region 5 frequency distributions of isolated flashes per km to the nearest flash. April, July and October

The months April, July, and October have been chosen to represent the seasons spring, summer, and fall respectively. In the frequency distribution, Figure 8, July represents summer and has the most flashes, October represents the fall and has the least, while April, which represents the spring, is in the middle. The most notable feature in this distribution is the large

spike each month has at 18 km. This is due to the constraint that if the nearest flash is within 17 km, then the isolated flash becomes part of the cluster the nearest flash. Some isolated flashes

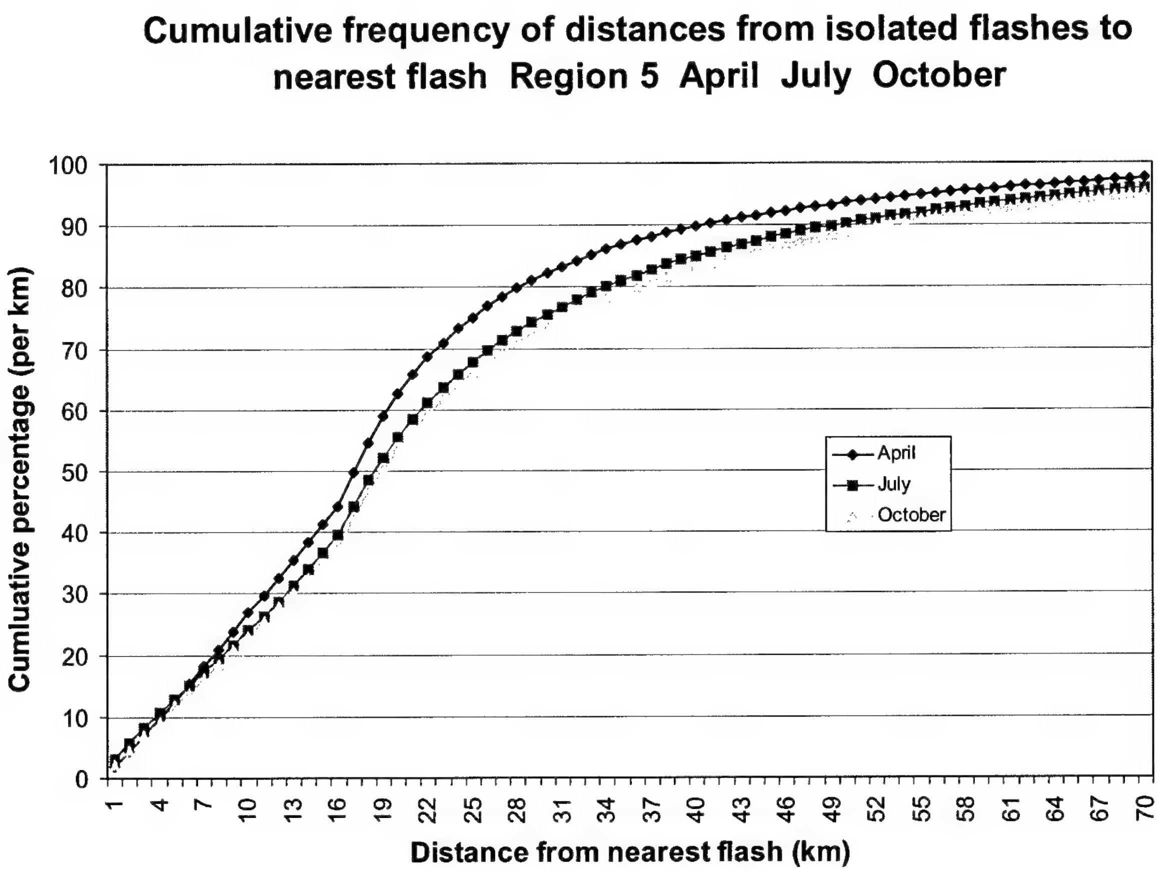

Figure 10 . Region 5 cumulative frequency distribution of isolated flashes per km from the nearest flash April, July, and October.

are within 17 km of another flash, but the flash does not fall within plus or minus 15 minutes. The isolated flashes are either too far from another flash in distance or time, or are both too far in distance and time from another flash to be added to a cluster.

To be 90% sure a "lone" flash would not strike at a particular distance from the it's nearest neighbor, then for this example, you could go to the historical data in the Figure 9 and depending on the season figure out the safe distance. The distance would depend on region and

on season. In this example, for the month of July, you would need to be 49 km from a pervious flash to be 90% sure a lone flash wouldn't strike at that distance.

4.4 Normalized flash density by region

The information presented in this section refers to the normalized flash density for Region 5. The probability of a flash striking a particular location in circle around a cluster center or isolated flash might be useful information. This probability takes into account the fact, the area of a circle increases significantly as one moves away from the center point. The probability of a flash striking a particular place in a circle will decrease by a factor of r^{-2}. In Figure 6 person 1 has a much greater chance of being struck by lightning than person 2, because the area of the circle where a flash may strike increases by the radius squared and when the flash densities are calculated the probabilities decrease substantially.

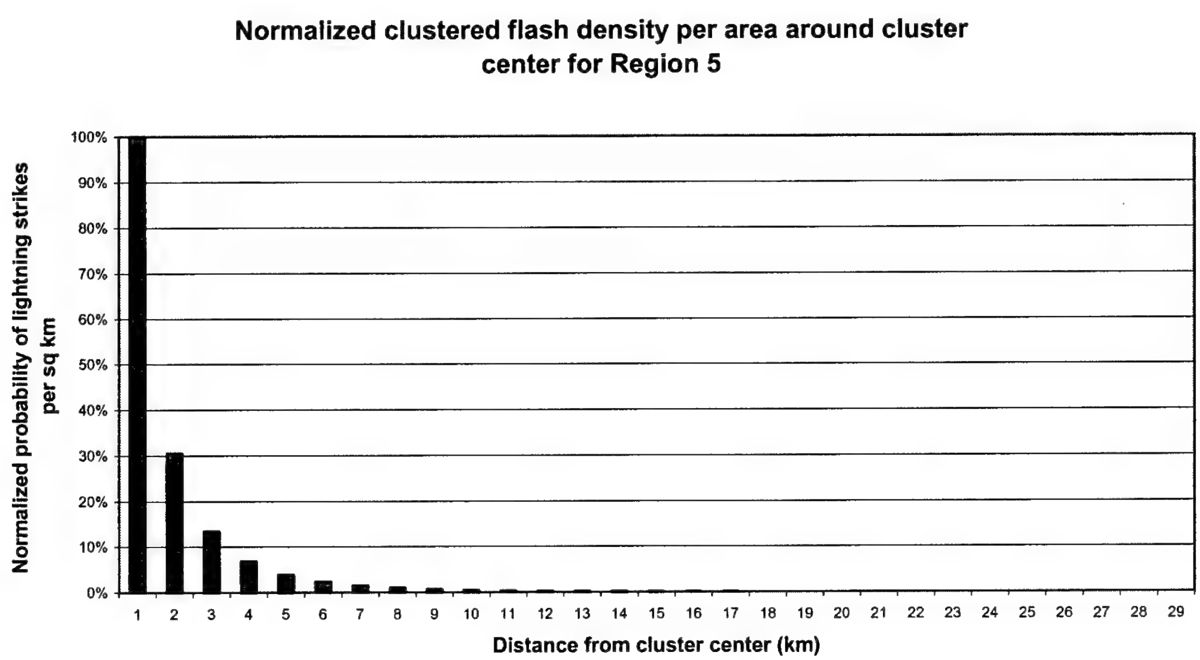

Figure 11. Normalized clustered flash density per area for Region 5. The vertical axis is probability of lightning striking in a particular location in a circular area around the clustered center at a particular distance normalized by the value in the first kilometer of radius for this region.

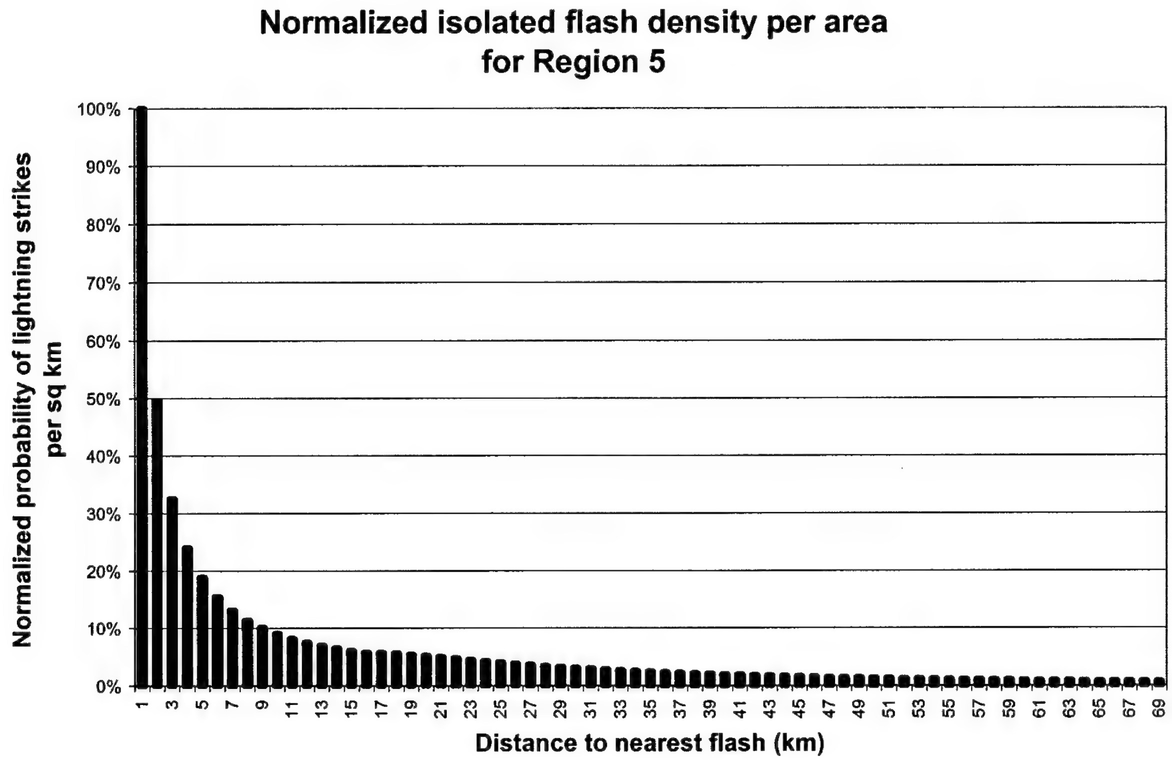

Figure 12. Normalized isolated flash density per area for Region 1. Probability of lightning striking in a particular location in a circular area around the isolated flash normalized by the value in the first kilometer of radius for this region.

The distributions of the clustered and isolated flashes in Figures 11 and 12, display the normalized flash densities per area for Region 5. All regions were normalized by the values in the first kilometer of radius to allow meaningful comparisons. The graph of the clustered flashes show the flash density decreases to less than 5% at 5 km. This signifies that flashes grouped or clustered with other flashes are not likely to strike an individual's specific location from the center of the cluster of flashes much beyond a circle with radius 5 km. The isolated flash density however, decreases more slowly with distance from an isolated flash. After about 19 km the isolated flash density drops below 5%. There is an 11% chance of an isolated flash striking an individual in a circle of radius of 9 km.

5. Conclusions

5.1 Conclusions

This research effort used more lighting data, over larger areas, and for longer times than any previous study. Lighting data for almost the entire continental United States was studied for March through November of each year from 1995-99, excluding October and November of 1999. During this research effort approximately 90 million flashes were grouped according to temporal and spatial constraints and then studied. Previous studies used only a few hours' worth of data or limited their research to a few thunderstorms. The distance between successive flash method used in this research handled the large amounts of lightning data with relative ease and provided output for six different regions in the continental United States for the spring, summer, and fall. This output provides a historical set of lightning data, which can be used to find the probability of lightning striking at a particular distance from a given point for a region and time of year.

The most critical conclusion of this research is that currently, it is not possible to select one safe distance. The distance criterion required for safety depends on region and season. For example, Region 5, which includes Florida, Georgia, and South Carolina, the cumulative frequency distributions demonstrate that between 68% and 79% of the lightning in a cluster happens within 5 nautical miles (9.26 km) of the lightning cluster center. This means anywhere from 32% to 21% of the lightning occurs at distances greater than 5 nautical miles (9.26 km), which is outlined in AFOSH 91-100 as a safe distance from lightning. Similar results can be found for each region listed in Appendix B.

When considering safety issues, the flashes not clustered must also be considered. Studying isolated flashes was a large part of this research effort because a large percentage of the

clusters consisted of isolated or single flash clusters. However only a small percentage of the overall number of flashes reaching the ground were not paired or clustered.

The number of isolated flash may be a small percentage of the total number of flashes studied in this research, but these outliers are significant in the sense that each isolated flash was a CG lighting flash and did strike somewhere. Isolated flashes could be considered more dangerous than flashes happening in a group or with a particular thunderstorm, because they are may seem to come unexpectedly out of the blue, or be a one-time occurrence. For these reasons the outlying or isolated flashes were scrutinized during this research, and not discarded as in previous studies. These isolated flashes comprised between 11% and 26% of the total number of clusters, or 1% to 9% of the total number of flashes. For Region 5, between 80% an 76% of the isolated flashes strike the ground beyond 5 nautical miles (9.26 km) from the next nearest flash. Examining the flash density per circular area around a given point provided insight into the probability of a clustered or isolated flash striking a particular location. The probability of an isolated flash striking an exact location does not drop below 5% until 19 km for the isolated flashes. The Air Force safety rule of 5 nautical miles does not seem adequate.

Danger from lightning strikes cannot be totally eliminated, because some work will still have to be accomplished outdoors. Shutting down operations until the threat of lightning injury is reduced to zero is simply unrealistic. As such, using the historical lightning data in the cumulative frequency distributions coupled with a set acceptable level of risk could prove useful to managers and those planning operations. The probabilities provide the ability to weigh the risk to personnel against the operational needs, and will allow managers to formulate decisions that minimize that risk.

5.2 Future research recommendations

Further research on the distance lightning travels and other lightning characteristics should be done. If the distance between successive flash method is used to group lightning data, then the effects of allowing the time constraint to vary, instead of remaining fixed at 12 minutes, could prove valuable. Then time length as well as the distance distributions could be studied. Also evaluating the distance between each successive flash in the clusters might better define safe distances. Other characteristics, such as polarity, multiplicity, and peak current of both clustered and isolated flashes would also be worth examining. Studying the characteristics of the clustered flashes, such as peak current or polarity, and then examining the data for correlations between clustered flashes and isolated flashes would also be a valuable research project.

Another worthy avenue of research would be coupling lightning flash data and WSR-88D data in an attempt to validate the clustering algorithm in this study or look for a correlation between lightning data and storm parameters. Allowing storm parameters to be correlated to lightning data could lead to insights about spatial and temporal characteristics of lightning. Finally, a new lightning measurement system based on Global Positioning System technology (Krehbiel et al. 2000) may provide a future data set for analysis.

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Appendix A. Examples output files.

Appendix A contains hard copies of the six types of output files described in Section 3.4. The prefixes to the files are **flash, fnew, f, iso, stat, snew**. Each prefix has an identifier attached to the end, which consists of year, month, day, and region.

Table A-1. **Flash** output file for 10 July 1996 for region 5
flash960710r5.txt

Date	Time	Cluster #	Latitude	Longitude	Current	Multiplicity
07/10/96	10:45:05	1	0.60870	-1.34700	-32.4	1
07/10/96	10:50:21	1	0.60771	-1.34790	-29.0	1
07/10/96	10:54:15	2	0.60340	-1.35341	-27.0	1
07/10/96	10:55:11	2	0.60446	-1.35291	-22.9	1
07/10/96	10:56:45	2	0.60442	-1.35220	-79.6	3
07/10/96	10:58:03	2	0.60546	-1.35237	-68.1	1
07/10/96	11:00:06	2	0.60652	-1.35203	-58.5	1
07/10/96	11:01:04	2	0.60673	-1.35407	-58.3	1
07/10/96	11:05:06	2	0.60595	-1.35248	-50.1	3
07/10/96	11:05:49	2	0.60519	-1.35297	-99.2	1
07/10/96	11:06:27	3	0.60861	-1.34644	-15.5	2
07/10/96	11:09:01	3	0.60910	-1.34642	-22.9	1
07/10/96	11:07:52	4	0.60458	-1.35354	-21.0	3
07/10/96	11:09:30	4	0.60538	-1.35185	-40.4	3
07/10/96	11:10:03	4	0.60445	-1.35375	-29.1	2
07/10/96	11:10:48	4	0.60433	-1.35386	-38.4	3
07/10/96	11:11:18	4	0.60567	-1.35134	-53.8	2
07/10/96	11:12:27	4	0.60593	-1.35188	-54.2	5
07/10/96	11:13:54	4	0.60548	-1.35092	-77.3	4
07/10/96	11:14:22	4	0.60523	-1.35284	-34.0	1
07/10/96	11:15:05	4	0.60443	-1.35285	-20.6	4
07/10/96	11:15:16	4	0.60417	-1.35174	49.6	1
07/10/96	11:15:47	4	0.60588	-1.35121	-73.2	2
07/10/96	11:16:09	4	0.60448	-1.35229	-31.5	3
07/10/96	11:16:49	4	0.60425	-1.35224	-80.2	3
07/10/96	11:17:27	4	0.60460	-1.35190	-82.0	5
07/10/96	11:18:11	4	0.60512	-1.35243	-13.6	2
07/10/96	11:19:19	4	0.60472	-1.35194	-50.6	5
07/10/96	11:20:00	5	0.60625	-1.35209	-16.7	1
07/10/96	11:21:14	5	0.60415	-1.35049	16.7	1
07/10/96	11:21:23	5	0.60484	-1.35202	-16.4	2
07/10/96	11:22:35	5	0.60603	-1.35088	-51.4	3
07/10/96	11:22:53	5	0.60479	-1.35179	-16.6	3
07/10/96	11:23:33	5	0.60454	-1.35192	-87.2	4
07/10/96	11:23:34	5	0.60471	-1.35133	-27.9	1
07/10/96	11:24:11	5	0.60528	-1.34939	-92.3	1
07/10/96	11:24:11	5	0.60448	-1.35123	-86.0	4
07/10/96	11:24:59	5	0.60454	-1.35151	-63.3	1
07/10/96	11:26:04	5	0.60542	-1.35203	-18.9	1
07/10/96	11:26:22	5	0.60363	-1.35248	-50.3	1
07/10/96	11:27:15	5	0.60461	-1.35131	-69.4	4
07/10/96	11:27:54	5	0.60361	-1.35153	-133.3	2
07/10/96	11:28:27	5	0.60315	-1.35043	19.4	1
07/10/96	11:28:59	5	0.60389	-1.35127	-168.4	4
07/10/96	11:29:48	5	0.60420	-1.35108	-172.3	3
07/10/96	11:30:37	5	0.60529	-1.35229	-29.7	2
07/10/96	11:30:37	5	0.60544	-1.35248	-21.0	1
07/10/96	11:31:51	5	0.60432	-1.35084	20.4	1
07/10/96	11:31:58	5	0.60474	-1.35215	-32.7	1
07/10/96	11:24:34	6	0.60945	-1.34499	-36.8	1
07/10/96	11:30:40	7	0.57831	-1.49269	-12.3	1

Table A-2. **stat** output file for 10 July 1996 for region 5
stat960710r5.txt

Date	Time	Cluster#	count	avg_lat	avg_lon	positive	negative	std_dev
07/10/96	10:45:05	1	2	34.847	-77.203	0.0	-32.4	0.000
07/10/96	10:54:15	2	8	34.679	-77.510	0.0	-99.2	3.896
07/10/96	11:06:27	3	2	34.885	-77.145	0.0	-22.9	0.000
07/10/96	11:07:52	4	16	34.659	-77.480	49.6	-82.0	1.560
07/10/96	11:20:00	5	21	34.645	-77.433	20.4	-172.3	3.141
07/10/96	11:24:34	6	1	34.919	-77.062	0.0	-36.8	0.000
07/10/96	11:30:40	7	1	33.135	-85.525	0.0	-12.3	0.000
07/10/96	11:35:50	8	5	34.608	-77.438	32.3	-146.1	2.422
07/10/96	11:47:24	9	3	34.636	-77.394	0.0	-100.4	0.891
07/10/96	12:08:46	10	1	27.386	-85.188	0.0	-18.4	0.000
07/10/96	12:20:34	11	1	27.479	-85.345	0.0	-92.7	0.000
07/10/96	12:44:13	12	9	25.023	-86.140	0.0	-34.4	0.922
07/10/96	12:50:56	13	1	25.452	-87.728	0.0	-24.6	0.000
07/10/96	13:08:13	14	6	25.440	-87.708	0.0	-32.6	1.082
07/10/96	13:23:05	15	1	27.259	-85.356	0.0	-22.5	0.000
07/10/96	13:41:23	16	10	25.371	-87.414	0.0	-110.5	2.036
07/10/96	13:54:00	17	3	25.356	-87.383	0.0	-65.5	0.723
07/10/96	14:02:30	18	1	26.964	-85.722	0.0	-32.3	0.000
07/10/96	14:07:07	19	9	27.073	-85.547	0.0	-125.9	0.647
07/10/96	14:11:32	20	1	25.356	-87.388	0.0	-43.2	0.000
07/10/96	14:19:56	21	3	26.929	-85.680	0.0	-60.2	0.556
07/10/96	14:23:56	22	1	27.031	-85.503	0.0	-38.6	0.000
07/10/96	14:27:23	23	5	25.473	-87.404	0.0	-36.2	2.624
07/10/96	14:31:42	24	1	25.273	-87.451	0.0	-19.6	0.000
07/10/96	14:36:40	25	4	34.137	-77.322	0.0	-68.0	2.785
07/10/96	14:40:19	26	6	25.447	-87.445	0.0	-48.5	1.224
07/10/96	14:46:15	27	3	26.774	-85.761	0.0	-223.5	0.270
07/10/96	14:49:28	28	8	34.145	-77.346	0.0	-127.8	3.484
07/10/96	14:50:56	29	1	34.343	-77.607	35.7	0.0	0.000
07/10/96	14:52:31	30	11	25.581	-87.414	0.0	-184.1	2.873
07/10/96	14:59:06	31	1	34.091	-77.512	0.0	-100.1	0.000
07/10/96	14:59:10	32	14	26.716	-85.779	0.0	-112.4	2.610
07/10/96	15:01:00	33	13	34.275	-77.087	0.0	-108.5	1.849
07/10/96	15:02:41	34	1	26.078	-87.693	0.0	-120.3	0.000
07/10/96	15:03:25	35	1	26.636	-86.000	0.0	-100.0	0.000
07/10/96	15:04:32	36	19	25.554	-87.435	0.0	-142.9	2.376
07/10/96	15:11:52	37	6	26.640	-85.788	0.0	-122.6	1.026
07/10/96	15:14:25	38	3	34.324	-77.034	0.0	-129.0	0.297
07/10/96	15:16:55	39	12	25.516	-87.455	0.0	-117.0	2.533
07/10/96	15:17:05	40	2	28.530	-85.722	0.0	-19.0	0.000
07/10/96	15:30:23	41	1	25.166	-87.304	0.0	-29.0	0.000
07/10/96	15:30:23	42	1	26.632	-87.656	0.0	-25.2	0.000
07/10/96	15:33:21	43	2	25.506	-87.433	0.0	-139.0	0.000
07/10/96	15:40:50	44	1	25.672	-87.449	0.0	-98.6	0.000
07/10/96	15:41:37	45	8	28.416	-85.798	0.0	-29.0	0.699
07/10/96	15:41:48	46	3	25.387	-87.244	0.0	-73.7	0.958
07/10/96	15:44:51	47	1	26.731	-85.865	0.0	-19.3	0.000
07/10/96	15:45:04	48	1	25.146	-87.315	0.0	-21.8	0.000
07/10/96	15:48:23	49	2	25.455	-86.700	0.0	-28.7	0.000
07/10/96	15:55:00	50	1	25.435	-87.444	0.0	-43.3	0.000

Table A-3. **iso** output file for 10 July 1996 for region 5
iso960710r5.txt

```
number of isolated flashes        139
total # of clusters (n) =       567.000
total # of flashes (nn) =       6694.00
cumluative distance D      7978.62
mean distance        57.4001
median distance        21.1555

% LE 50km =          75.5396
% LE 40km =          69.7842
% LE 20km =          45.3237
% LE 10km =          21.5827

SINGLE FLASH CLUSTER                              DISTANCE NEAREST FLASH
07/10/96 11:24:34  34.919  -77.062   6  -36.8    35.131 07/10/96 11:24:11  34.680  -77.314   5
07/10/96 11:30:40  33.135  -85.525   7  -12.3   757.307 07/10/96 11:46:19  34.546  -77.563   8
07/10/96 12:08:46  27.386  -85.188  10  -18.4     0.000 07/10/96 12:08:46  27.386  -85.189  10
07/10/96 12:20:34  27.479  -85.345  11  -92.7     0.000 07/10/96 12:20:34  27.479  -85.345  11
07/10/96 12:50:56  25.452  -87.728  13  -24.6   164.049 07/10/96 12:45:05  25.026  -86.163  12
07/10/96 13:23:05  27.259  -85.356  15  -22.5   302.928 07/10/96 13:08:13  25.473  -87.673  14
07/10/96 14:02:30  26.964  -85.722  18  -32.3    19.388 07/10/96 14:14:34  27.069  -85.566  19
07/10/96 14:11:32  25.356  -87.388  20  -43.2   243.325 07/10/96 14:19:56  26.912  -85.683  21
07/10/96 14:23:56  27.031  -85.503  22  -38.6    19.950 07/10/96 14:25:21  26.938  -85.676  21
07/10/96 14:31:42  25.273  -87.451  24  -19.6    14.988 07/10/96 14:45:36  25.408  -87.447  26
07/10/96 14:50:56  34.343  -77.607  29   35.7    28.643 07/10/96 14:56:40  34.147  -77.405  28
07/10/96 14:59:06  34.091  -77.512  31 -100.1    11.632 07/10/96 14:56:40  34.147  -77.405  28
07/10/96 15:02:41  26.078  -87.693  34 -120.3    50.751 07/10/96 14:59:16  25.678  -87.447  30
07/10/96 15:03:25  26.636  -86.000  35 -100.0    18.885 07/10/96 15:23:37  26.645  -85.810  37
07/10/96 15:30:23  25.166  -87.304  41  -29.0     2.417 07/10/96 15:45:04  25.147  -87.315  48
07/10/96 15:30:23  26.632  -87.656  42  -25.2   108.579 07/10/96 15:40:50  25.673  -87.449  44
07/10/96 15:40:50  25.672  -87.449  44  -98.6    18.149 07/10/96 15:33:21  25.512  -87.412  43
07/10/96 15:44:51  26.731  -85.865  47  -19.3   163.257 07/10/96 15:50:17  25.463  -86.695  49
07/10/96 15:45:04  25.146  -87.315  48  -21.8     2.466 07/10/96 15:30:23  25.166  -87.304  41
07/10/96 15:55:00  25.435  -87.444  50  -43.3    19.168 07/10/96 15:57:50  25.482  -87.260  52
```

Table A-4. **fnew** output file for 10 July 1996 for region 5
fnew960710r5.txt

Date	Time	Cluster #	Latitude	Longitude	current	multiplicity
07/10/96	10:45:05	1	0.60870	-1.34700	-32.4	1
07/10/96	10:50:21	1	0.60771	-1.34790	-29.0	1
07/10/96	10:54:15	2	0.60340	-1.35341	-27.0	1
07/10/96	10:55:11	2	0.60446	-1.35291	-22.9	3
07/10/96	10:58:03	2	0.60546	-1.35237	-68.1	1
07/10/96	11:00:06	2	0.60652	-1.35203	-58.5	1
07/10/96	11:01:04	2	0.60673	-1.35407	-58.3	1
07/10/96	11:05:06	2	0.60595	-1.35248	-50.1	3
07/10/96	11:05:49	2	0.60519	-1.35297	-99.2	1
07/10/96	11:06:27	3	0.60861	-1.34644	-15.5	2
07/10/96	11:09:01	3	0.60910	-1.34642	-22.9	1
07/10/96	11:07:52	4	0.60458	-1.35354	-21.0	3
07/10/96	11:09:30	4	0.60538	-1.35185	-40.4	3
07/10/96	11:10:03	4	0.60445	-1.35375	-29.1	2
07/10/96	11:10:48	4	0.60433	-1.35386	-38.4	3
07/10/96	11:11:18	4	0.60567	-1.35134	-53.8	2
07/10/96	11:12:27	4	0.60593	-1.35188	-54.2	5
07/10/96	11:13:54	4	0.60548	-1.35092	-77.3	4
07/10/96	11:14:22	4	0.60523	-1.35284	-34.0	1
07/10/96	11:15:05	4	0.60443	-1.35285	-20.6	4
07/10/96	11:15:16	4	0.60417	-1.35174	49.6	1
07/10/96	11:15:47	4	0.60588	-1.35121	-73.2	2
07/10/96	11:16:09	4	0.60448	-1.35229	-31.5	3
07/10/96	11:16:49	4	0.60425	-1.35224	-80.2	3
07/10/96	11:17:27	4	0.60460	-1.35190	-82.0	5
07/10/96	11:18:11	4	0.60512	-1.35243	-13.6	2
07/10/96	11:19:19	4	0.60472	-1.35194	-50.6	5
07/10/96	11:20:00	5	0.60625	-1.35209	-16.7	1
07/10/96	11:21:14	5	0.60415	-1.35049	16.7	1
07/10/96	11:21:23	5	0.60484	-1.35202	-16.4	2
07/10/96	11:22:35	5	0.60603	-1.35088	-51.4	3
07/10/96	11:22:53	5	0.60479	-1.35179	-16.6	3
07/10/96	11:23:33	5	0.60454	-1.35192	-87.2	4
07/10/96	11:23:34	5	0.60471	-1.35133	-27.9	1
07/10/96	11:24:11	5	0.60528	-1.34939	-92.3	1
07/10/96	11:24:11	5	0.60448	-1.35123	-86.0	4
07/10/96	11:24:59	5	0.60454	-1.35151	-63.3	1
07/10/96	11:26:04	5	0.60542	-1.35203	-18.9	1
07/10/96	11:26:22	5	0.60363	-1.35248	-50.3	1
07/10/96	11:27:15	5	0.60461	-1.35131	-69.4	4
07/10/96	11:27:54	5	0.60361	-1.35153	-133.3	2
07/10/96	11:28:27	5	0.60315	-1.35043	19.4	1
07/10/96	11:28:59	5	0.60389	-1.35127	-168.4	4
07/10/96	11:29:48	5	0.60420	-1.35108	-172.3	3
07/10/96	11:30:37	5	0.60529	-1.35229	-29.7	2
07/10/96	11:30:37	5	0.60544	-1.35248	-21.0	1
07/10/96	11:31:51	5	0.60432	-1.35084	20.4	1
07/10/96	11:31:58	5	0.60474	-1.35215	-32.7	1
07/10/96	11:24:34	6	0.60945	-1.34499	-36.8	1
07/10/96	11:30:40	7	0.57831	-1.49269	-12.3	1

Table A-5. **snew** output file for 10 July 1996 for region 5
snew960710r5.txt

Date	Time	cluster #	count	avg_lat	avg_lon	positive	negative	std_dev
07/10/96	10:45:05	1	2	34.848	-77.203	0.0	-32.4	0.000
07/10/96	10:54:15	2	8	34.679	-77.510	0.0	-99.2	4.051
07/10/96	11:06:27	3	2	34.885	-77.145	0.0	-22.9	0.000
07/10/96	11:07:52	4	16	34.659	-77.480	49.6	-82.0	2.458
07/10/96	11:20:00	5	21	34.645	-77.433	20.4	-172.3	3.450
07/10/96	11:24:34	6	1	34.919	-77.062	0.0	-36.8	0.000
07/10/96	11:30:40	7	1	33.135	-85.525	0.0	-12.3	0.000
07/10/96	11:35:50	8	5	34.608	-77.438	32.3	-146.1	4.532
07/10/96	11:47:24	9	3	34.636	-77.394	0.0	-100.4	0.899
07/10/96	12:08:46	10	1	27.386	-85.189	0.0	-18.4	0.000
07/10/96	12:20:34	11	1	27.479	-85.345	0.0	-92.7	0.000
07/10/96	12:44:13	12	9	25.023	-86.140	0.0	-34.4	0.946
07/10/96	12:50:56	13	1	25.452	-87.728	0.0	-24.6	0.000
07/10/96	13:08:13	14	6	25.440	-87.708	0.0	-32.6	1.201
07/10/96	13:23:05	15	1	27.259	-85.356	0.0	-22.5	0.000
07/10/96	13:41:23	16	10	25.371	-87.414	0.0	-110.5	2.000
07/10/96	13:54:00	17	3	25.356	-87.383	0.0	-65.5	1.944
07/10/96	14:02:30	18	1	26.964	-85.723	0.0	-32.3	0.000
07/10/96	14:07:07	19	9	27.073	-85.547	0.0	-125.9	0.794
07/10/96	14:11:32	20	1	25.356	-87.388	0.0	-43.2	0.000
07/10/96	14:19:56	21	3	26.929	-85.680	0.0	-60.2	0.530
07/10/96	14:23:56	22	1	27.031	-85.504	0.0	-38.6	0.000
07/10/96	14:27:23	23	5	25.473	-87.404	0.0	-36.2	2.466
07/10/96	14:36:40	25	4	34.137	-77.322	0.0	-68.0	4.126
07/10/96	14:31:42	26	7	25.422	-87.445	0.0	-48.5	5.196
07/10/96	14:46:15	27	3	26.774	-85.761	0.0	-223.5	0.148
07/10/96	14:49:28	28	9	34.139	-77.364	0.0	-127.8	5.169
07/10/96	14:50:56	29	1	34.343	-77.607	35.7	0.0	0.000
07/10/96	14:52:31	30	11	25.581	-87.414	0.0	-184.1	2.816
07/10/96	14:59:10	32	14	26.716	-85.779	0.0	-112.4	2.450
07/10/96	15:01:00	33	13	34.275	-77.087	0.0	-108.5	1.690
07/10/96	15:02:41	34	1	26.078	-87.693	0.0	-120.3	0.000
07/10/96	15:03:25	35	1	26.636	-86.000	0.0	-100.0	0.000
07/10/96	15:04:32	36	19	25.554	-87.435	0.0	-142.9	2.266
07/10/96	15:11:52	37	6	26.640	-85.788	0.0	-122.6	0.650
07/10/96	15:14:25	38	3	34.324	-77.034	0.0	-129.0	0.840
07/10/96	15:16:55	39	12	25.516	-87.455	0.0	-117.0	2.086
07/10/96	15:17:05	40	2	28.530	-85.722	0.0	-19.0	0.000
07/10/96	15:30:23	42	1	26.632	-87.656	0.0	-25.2	0.000
07/10/96	15:33:21	43	2	25.506	-87.433	0.0	-139.0	0.000
07/10/96	15:40:50	44	1	25.673	-87.449	0.0	-98.6	0.000
07/10/96	15:43:46	45	8	28.416	-85.798	0.0	-29.0	1.200
07/10/96	15:41:48	46	3	25.387	-87.244	0.0	-73.7	0.324
07/10/96	15:44:51	47	1	26.731	-85.866	0.0	-19.3	0.000
07/10/96	15:30:23	48	2	25.156	-87.310	0.0	-29.0	0.000
07/10/96	15:48:23	49	2	25.455	-86.700	0.0	-28.7	0.000
07/10/96	15:55:00	50	1	25.435	-87.444	0.0	-43.3	0.000
07/10/96	15:55:28	51	2	25.571	-87.737	0.0	-19.7	0.000
07/10/96	15:56:54	52	10	25.491	-87.227	0.0	-98.2	2.274
07/10/96	16:07:43	53	14	25.387	-86.683	0.0	-50.0	1.721

Table A-6. **f** output file for 10 July 1996 for region 5

f960710r5.txt

Date	Time	cluster #	Latitude	Longitude	current	multiplicity	distance
07/10/96	10:45:05	1	34.876	-77.177	-32.4	1	3.934
07/10/96	10:50:21	1	34.819	-77.229	-29.0	1	3.934
07/10/96	10:54:15	2	34.572	-77.545	-27.0	1	12.303
07/10/96	10:55:11	2	34.633	-77.516	-22.9	1	5.165
07/10/96	10:56:45	2	34.631	-77.475	-79.6	3	6.253
07/10/96	10:58:03	2	34.690	-77.485	-68.1	1	2.592
07/10/96	11:00:06	2	34.751	-77.466	-58.5	1	8.959
07/10/96	11:01:04	2	34.763	-77.582	-58.3	1	11.439
07/10/96	11:05:06	2	34.718	-77.491	-50.1	3	4.677
07/10/96	11:05:49	2	34.675	-77.519	-99.2	1	0.991
07/10/96	11:06:27	3	34.871	-77.145	-15.5	2	1.562
07/10/96	11:09:01	3	34.899	-77.144	-22.9	1	1.561
07/10/96	11:07:52	4	34.640	-77.552	-21.0	3	6.914
07/10/96	11:09:30	4	34.686	-77.455	-40.4	3	3.723
07/10/96	11:10:03	4	34.632	-77.564	-29.1	2	8.230
07/10/96	11:10:48	4	34.626	-77.570	-38.4	3	9.059
07/10/96	11:11:18	4	34.702	-77.426	-53.8	2	6.890
07/10/96	11:12:27	4	34.717	-77.457	-54.2	5	6.784
07/10/96	11:13:54	4	34.691	-77.402	-77.3	4	8.002
07/10/96	11:14:22	4	34.677	-77.512	-34.0	1	3.514
07/10/96	11:15:05	4	34.631	-77.513	-20.6	4	4.291
07/10/96	11:15:16	4	34.616	-77.449	49.6	1	5.562
07/10/96	11:15:47	4	34.714	-77.419	-73.2	2	8.324
07/10/96	11:16:09	4	34.634	-77.481	-31.5	3	2.795
07/10/96	11:16:49	4	34.621	-77.478	-80.2	3	4.267
07/10/96	11:17:27	4	34.641	-77.458	-82.0	5	2.867
07/10/96	11:18:11	4	34.671	-77.489	-13.6	2	1.487
07/10/96	11:19:19	4	34.648	-77.460	-50.6	5	2.212
07/10/96	11:20:00	5	34.736	-77.469	-16.7	1	10.647
07/10/96	11:21:14	5	34.615	-77.377	16.7	1	6.016
07/10/96	11:21:23	5	34.655	-77.465	-16.4	2	3.173
07/10/96	11:22:35	5	34.723	-77.400	-51.4	3	9.217
07/10/96	11:22:53	5	34.652	-77.452	-16.6	3	1.938
07/10/96	11:23:33	5	34.638	-77.459	-87.2	4	2.562
07/10/96	11:23:34	5	34.647	-77.426	-27.9	1	0.718
07/10/96	11:24:11	5	34.680	-77.314	-92.3	1	11.511
07/10/96	11:24:11	5	34.634	-77.420	-86.0	4	1.652
07/10/96	11:24:59	5	34.638	-77.436	-63.3	1	0.833
07/10/96	11:26:04	5	34.688	-77.466	-18.9	1	5.691
07/10/96	11:26:22	5	34.585	-77.491	-50.3	1	8.494
07/10/96	11:27:15	5	34.642	-77.424	-69.4	4	0.826
07/10/96	11:27:54	5	34.584	-77.437	-133.3	2	6.716
07/10/96	11:28:27	5	34.558	-77.374	19.4	1	11.028
07/10/96	11:28:59	5	34.600	-77.422	-168.4	4	5.014
07/10/96	11:29:48	5	34.618	-77.411	-172.3	3	3.539
07/10/96	11:30:37	5	34.681	-77.481	-29.7	2	5.930
07/10/96	11:30:37	5	34.689	-77.491	-21.0	1	7.310
07/10/96	11:31:51	5	34.625	-77.397	20.4	1	3.889
07/10/96	11:31:58	5	34.649	-77.472	-32.7	1	3.679
07/10/96	11:24:34	6	34.919	-77.062	-36.8	1	0.000

Appendix B. Clustered flash summary information for Regions 1, 2, 3, 4, and 6 by season

Region 1

Table B-1. Region 1 clustered flash summary statistics for individual months. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 1	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Mean (km)	4.92	5.52	6.03	6.68	7.26	6.74	6.27	5.71	4.26
Median (km)	4.24	4.66	4.89	5.40	5.81	5.44	5.02	4.83	3.63
Std Dev (km)	4.02	4.39	4.90	5.34	5.86	5.32	4.96	4.53	3.83
Variance (km^2)	16.16	19.28	24.00	28.52	34.32	28.34	24.59	20.51	14.70
Percentile at 9-km bin (%)	86.9	83.6	81.3	78.0	74.9	78.1	80.8	82.8	88.8

Table B-2. Region 1 clustered flash summary statistics for seasons. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 1	Spring	Summer	Fall
Number Flashes	430735	4065653	524311
Mean (km)	5.94	6.93	6.22
Median (km)	4.85	5.57	5.07
Std Deviation (km)	4.83	5.55	4.93
Variance (km^2)	23.31	30.83	24.28
Percentile at 9-km bin (%)	82.4	82.0	81.0

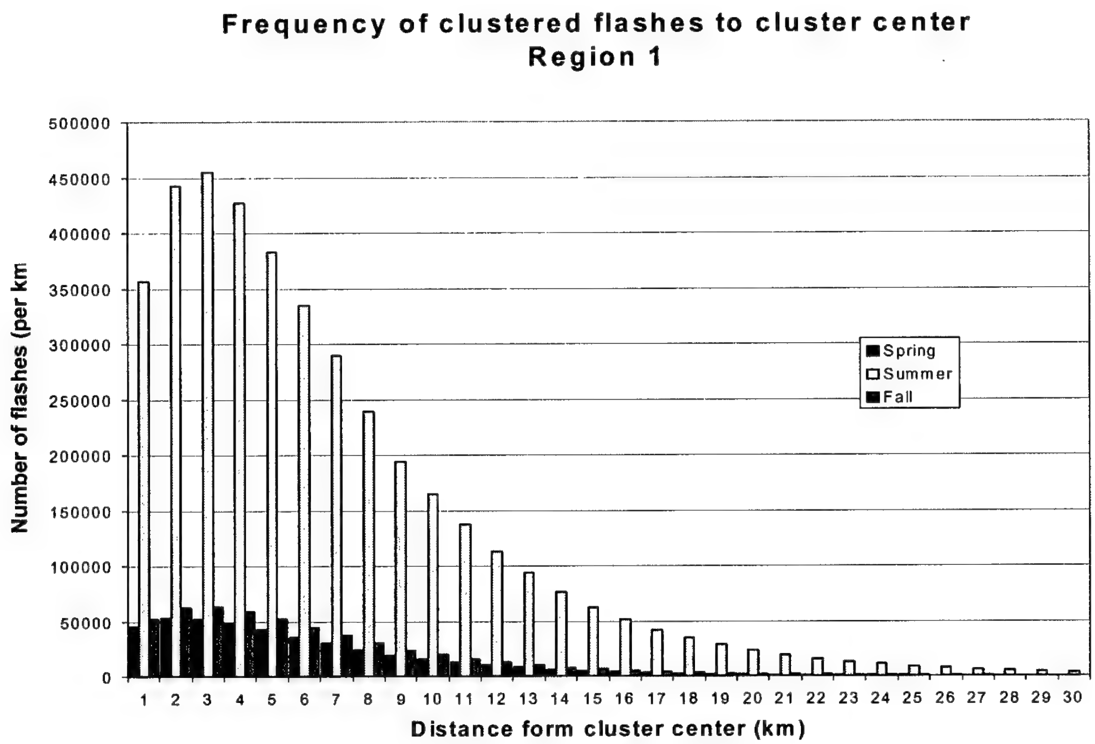

Figure B-1. Region 1 frequency distributions of flashes per km from cluster center. Frequencies for Spring, Summer, and Fall.

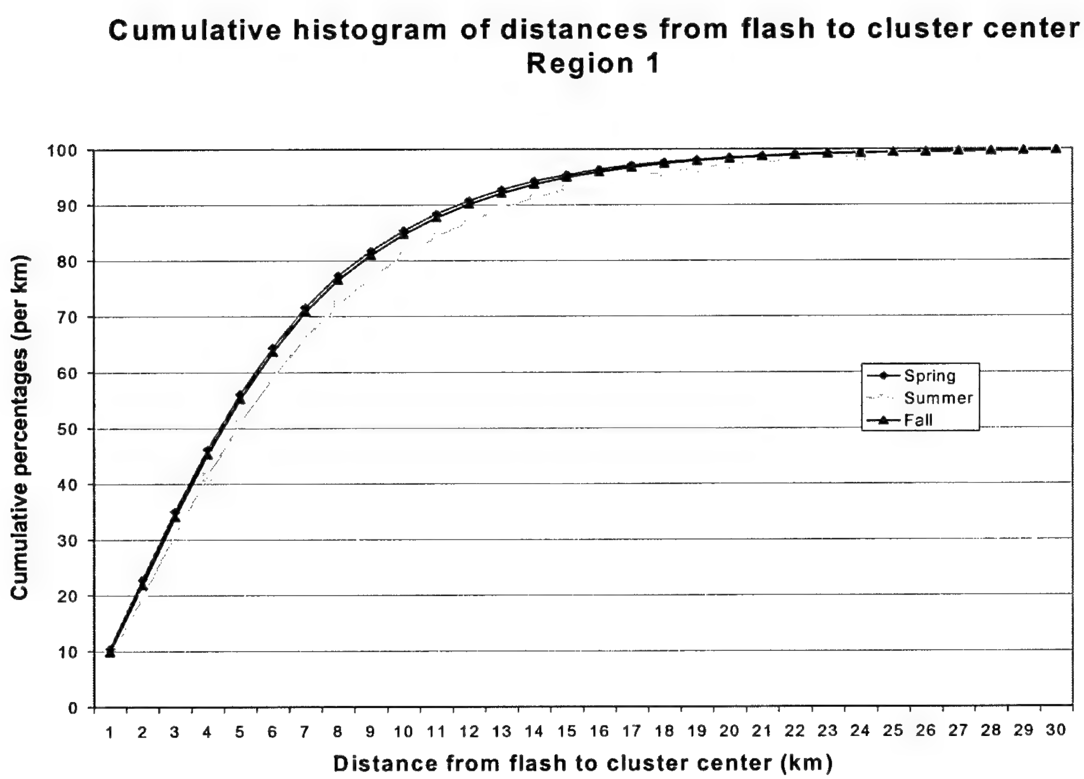

Figure B-1. Region 1 cumulative frequency distribution of clustered flashes per km from cluster center. Distributions for Spring, Summer, and Fall.

Region 2

Table B-3. Region 2 clustered flash summary statistics for individual months. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 2	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Mean (km)	4.75	4.86	5.80	6.43	6.30	6.11	5.98	6.60	5.09
Median (km)	3.84	3.94	4.60	5.12	4.97	4.80	4.76	5.30	4.19
Std Dev (km)	4.02	4.13	4.78	5.20	5.09	4.97	4.76	5.42	4.30
Variance (km^2)	16.13	17.04	22.89	27.03	25.91	24.74	22.63	29.42	18.48
Percentile at 9-km bin (%)	87.8	87.0	82.3	79.7	80.5	81.5	82.4	78.8	85.7

Table B-4. Region 2 clustered flash summary statistics for seasons. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 2	Spring	Summer	Fall
Number Flashes	656753	6717770	152908
Mean (km)	5.62	6.26	6.05
Median (km)	4.47	4.93	4.82
Std Deviation (km)	4.68	5.07	4.85
Variance (km^2)	21.94	25.70	23.50
Percentile at 9-km bin (%)	83.6	80.7	82.0

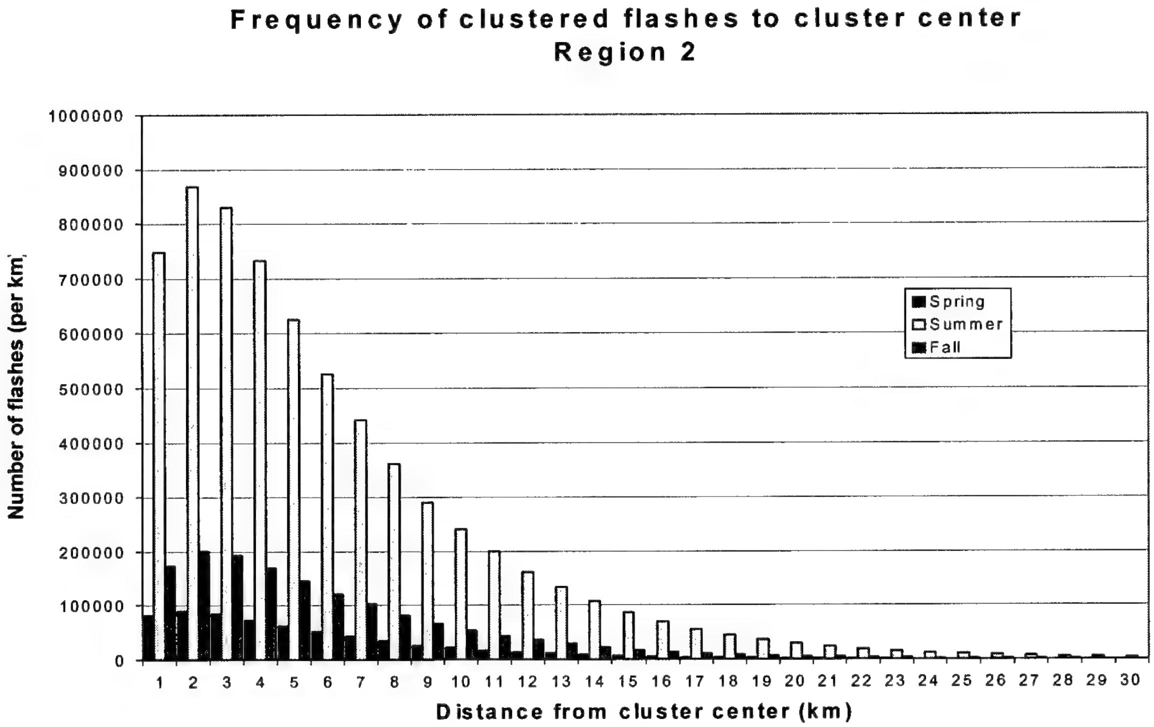

Figure B-3. Region 2 frequency distributions of flashes per km from cluster center. Frequencies for Spring, Summer, and Fall.

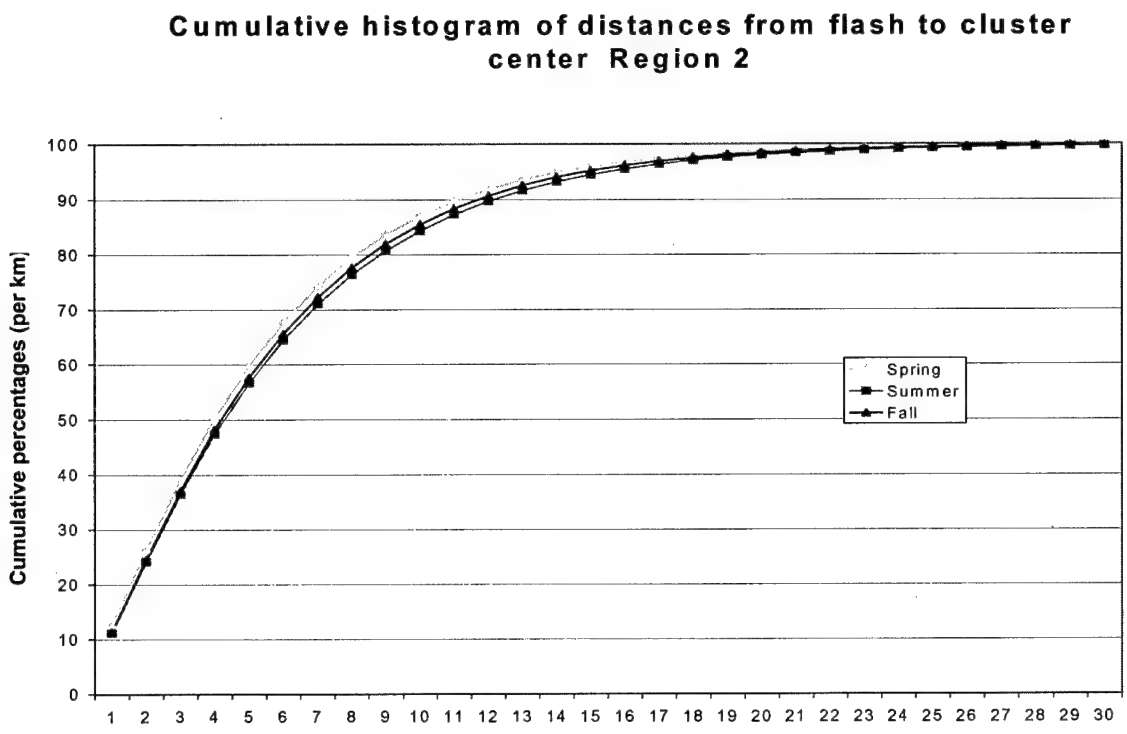

Figure B-4. Region 2 cumulative frequency distribution of clustered flashes per km from cluster center. Distributions Spring, Summer, and Fall.

Region 3

Table B-5. Region 3 clustered flash summary statistics for individual months. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 3	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Mean (km)	7.43	7.90	8.83	9.09	8.96	8.62	8.32	8.04	7.44
Median (km)	6.38	6.64	7.22	7.24	7.17	6.86	6.70	6.63	6.28
Std Dev (km)	5.36	5.84	6.76	7.26	7.06	6.86	6.51	6.16	5.57
Variance (km^2)	28.71	34.05	45.73	52.68	49.80	47.05	42.35	37.96	31.07
Percentile at 9-km bin (%)	71.2	70.9	65.8	64.8	65.5	67.2	68.9	70.1	73.0

Table B-6. Region 3 clustered flash summary statistics for seasons. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 3	Spring	Summer	Fall
Number Flashes	2988040	11424596	2159593
Mean (km)	8.55	8.90	8.22
Median (km)	7.03	7.10	6.66
Std Deviation (km)	6.51	7.07	6.40
Variance (km^2)	42.42	50.00	40.93
Percentile at 9-km bin (%)	67.3	65.8	69.3

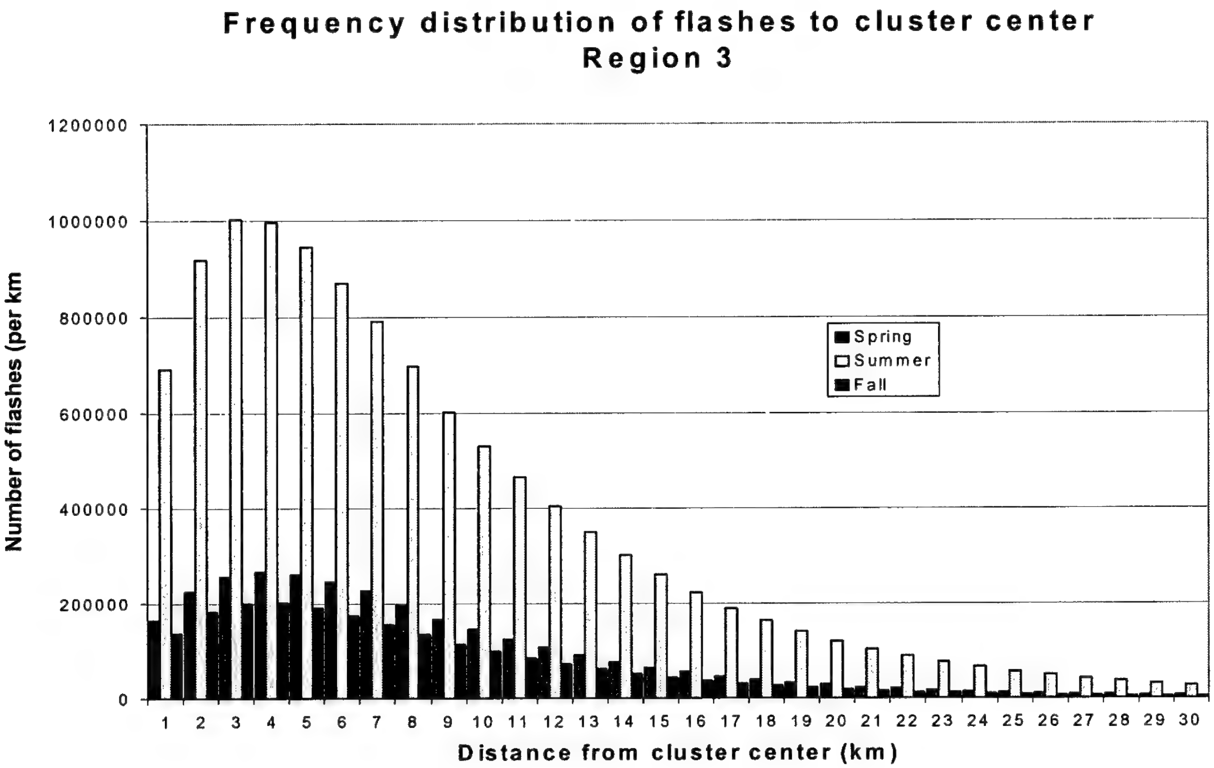

Figure B-5. Region 3 frequency distributions of flashes per km from cluster center. Frequencies for Spring, Summer, and Fall.

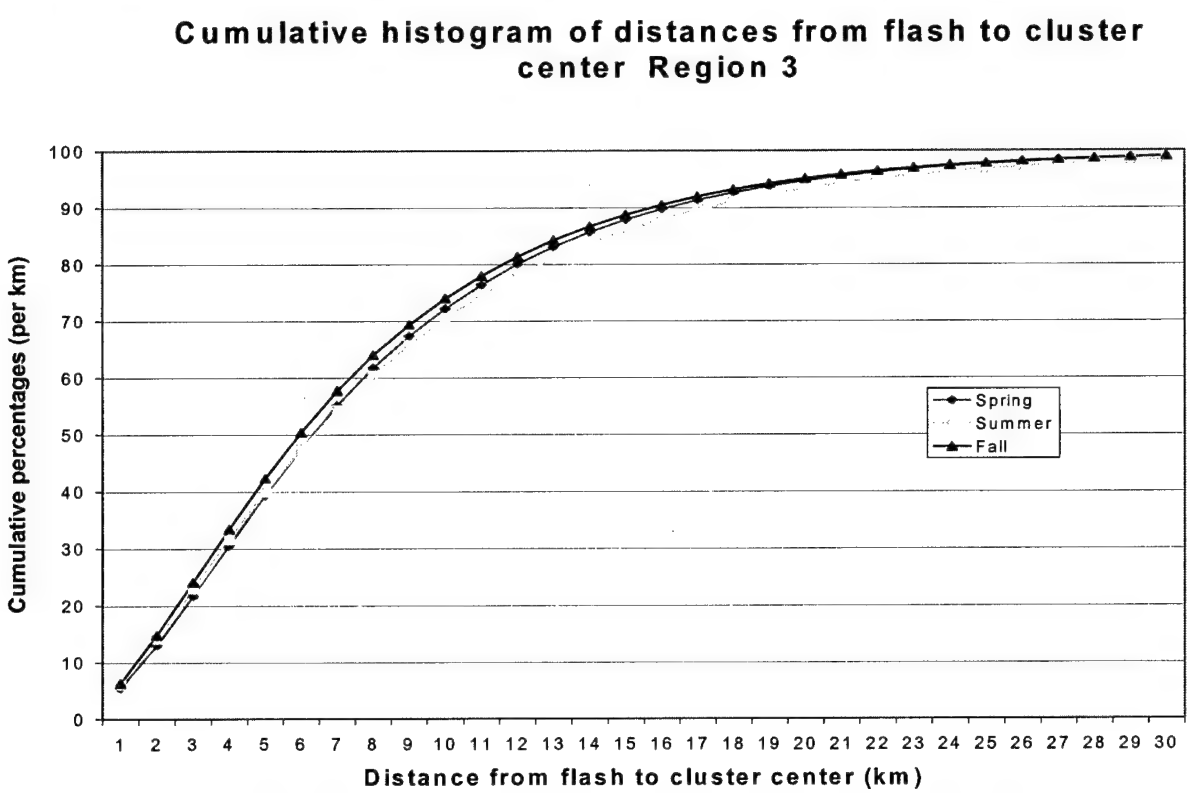

Figure B-6. Region 3 cumulative frequency distribution of clustered flashes per km from cluster center. Distributions for Spring, Summer, and Fall.

Region 4

Table B-7. Region 4 clustered flash summary statistics for individual months. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 4	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Mean (km)	8.43	9.20	9.10	8.46	7.89	7.33	7.63	8.39	8.49
Median (km)	6.99	7.57	7.38	6.68	6.06	5.60	5.96	6.78	7.01
Std Dev (km)	6.24	6.84	6.99	6.82	6.59	6.15	6.23	6.53	6.36
Variance (km^2)	39.00	46.74	48.90	46.46	43.44	37.82	38.83	42.58	40.49
Percentile at 9-km bin (%)	68.2	63.9	64.5	68.1	71.3	74.5	72.8	68.8	67.9

Table B-8. Region 4 clustered flash summary statistics for seasons. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 4	Spring	Summer	Fall
Number Flashes	7803513	14063274	3615701
Mean (km)	9.01	7.91	7.97
Median (km)	7.36	6.11	6.35
Std Deviation (km)	6.82	6.55	6.35
Variance (km^2)	46.56	42.93	40.28
Percentile at 9-km bin (%)	65.0	71.2	70.9

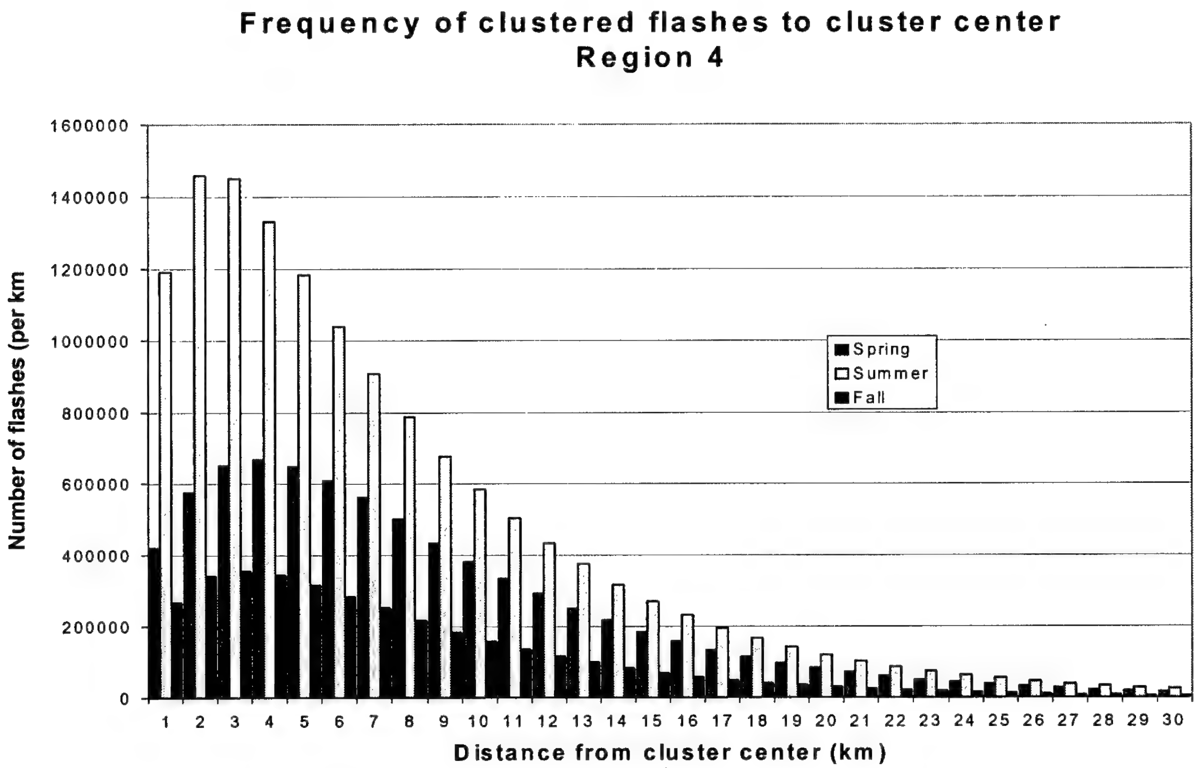

Figure B-7. Region 4 frequency distributions of flashes per km from cluster center. Frequencies for Spring, Summer, and Fall.

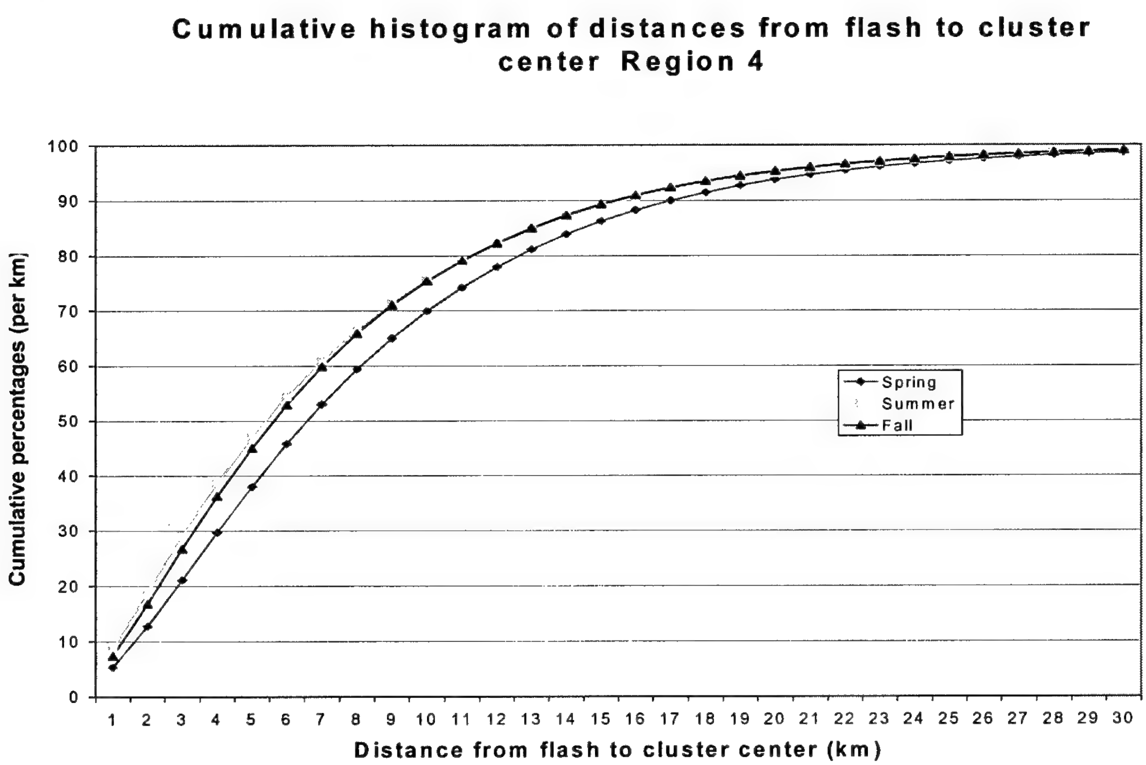

Figure B-8. Region cumulative frequency distribution of clustered flashes per km from cluster center. Distribution for Spring, Summer, and Fall.

Region 6

Table B-9. Region 6 clustered flash summary statistics for individual months. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 6	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Mean (km)	7.71	8.07	8.91	8.35	8.57	7.90	7.62	8.21	7.04
Median (km)	6.56	6.71	7.10	6.44	6.57	6.03	5.90	6.78	6.13
Std Dev (km)	5.62	6.04	7.05	6.97	7.16	6.66	6.39	6.26	5.15
Variance (km^2)	31.60	36.52	49.66	48.65	51.23	44.42	40.88	39.13	26.51
Percentile at 9-km bin (%)	72.2	70.3	66.0	69.3	68.1	71.7	73.4	68.7	75.6

Table B-10. Region 6 clustered flash summary statistics for seasons. Number of flashes, mean distance, median distance, standard deviation, variance, and percentile at 9-km bin.

Region 6	Spring	Summer	Fall
Number Flashes	3278341	10764828	992038
Mean (km)	8.65	8.33	7.66
Median (km)	6.97	6.39	6.01
Std Deviation (km)	6.76	6.98	6.33
Variance (km^2)	45.76	48.74	40.03
Percentile at 9-km bin (%)	67.4	69.4	73.0

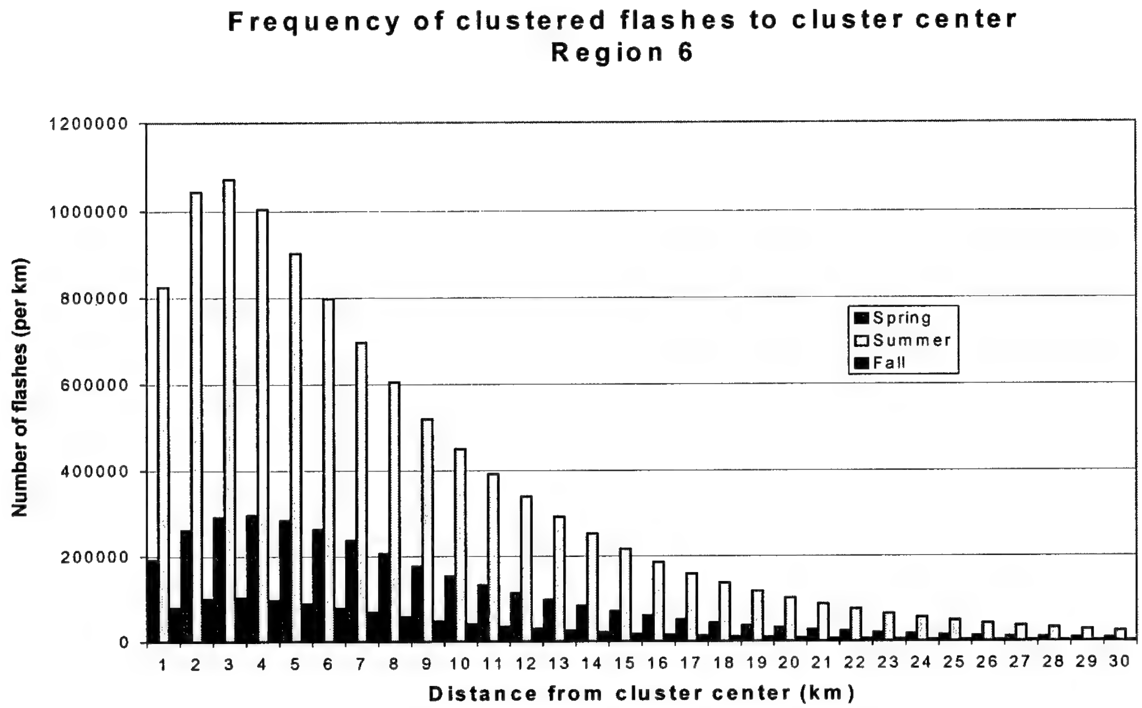

Figure B-9. Region 6 frequency distributions of flashes per km from cluster center. Frequencies for Spring, Summer, and Fall.

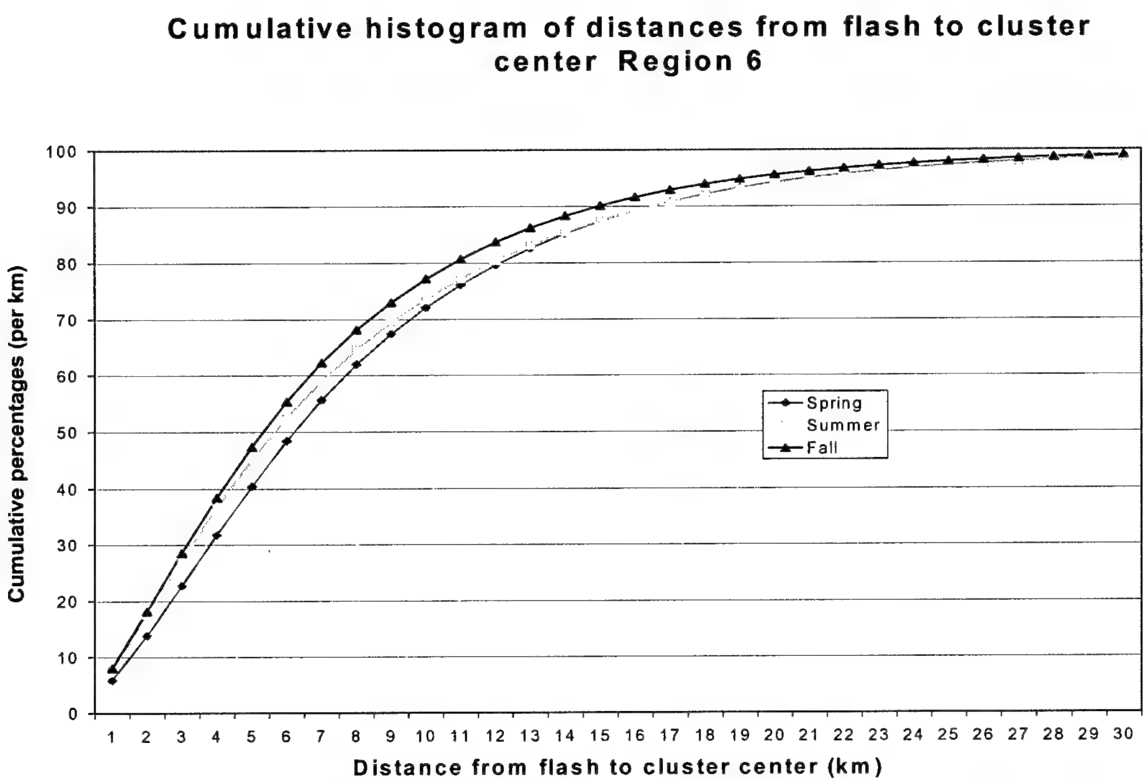

Figure B-10. Region 6 cumulative frequency distribution of clustered flashes per km from cluster center. Distribution for Spring, Summer and Fall.

Appendix C. Isolated flash summary information for Regions 1, 2, 3, 4, and 6 by seasons

Region 1

Table C-1. Region 1 isolated flash summary statistics for individual months. Mean distance, median distance, standard deviation, variance, and the distance at the 90th percentile.

Region 1	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Total # isolated flashes	1145	5298	25549	53607	56142	44446	21751	5874	2749
Mean (km)	47.82	14.72	53.83	41.08	76.77	56.62	111.84	62.04	73.07
Median (km)	21.44	10.34	20.12	24.01	22.99	19.43	48.00	17.39	30.69
Std Dev (km)	71.14	20.86	127.17	68.58	146.21	100.22	137.48	98.36	105.32
Variance (km^2)	5060	435	16173	4703	21377	10044	18901	9675	11091
90^{th} Percentile (km)	58	61	58	53	51	52	54	54	55

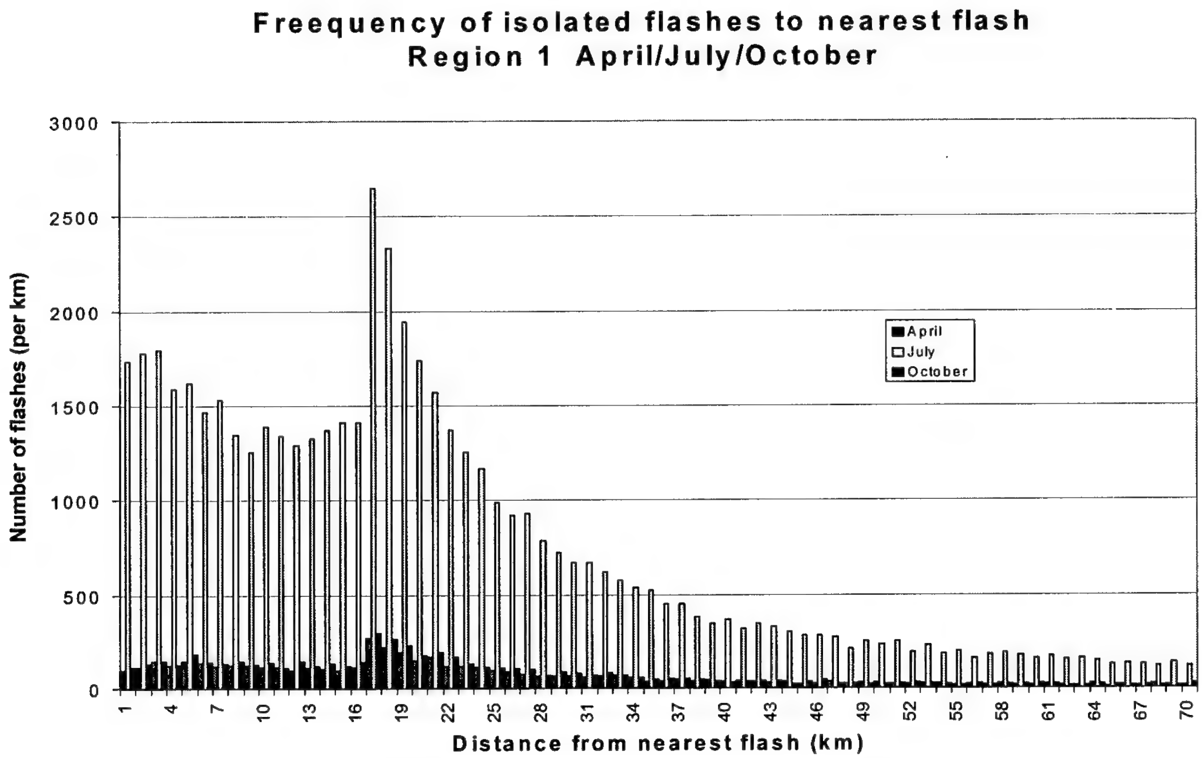

Figure C-1. Region 1 frequency distributions of isolated flashes per km to the nearest flash. Frequencies for April, July, and October.

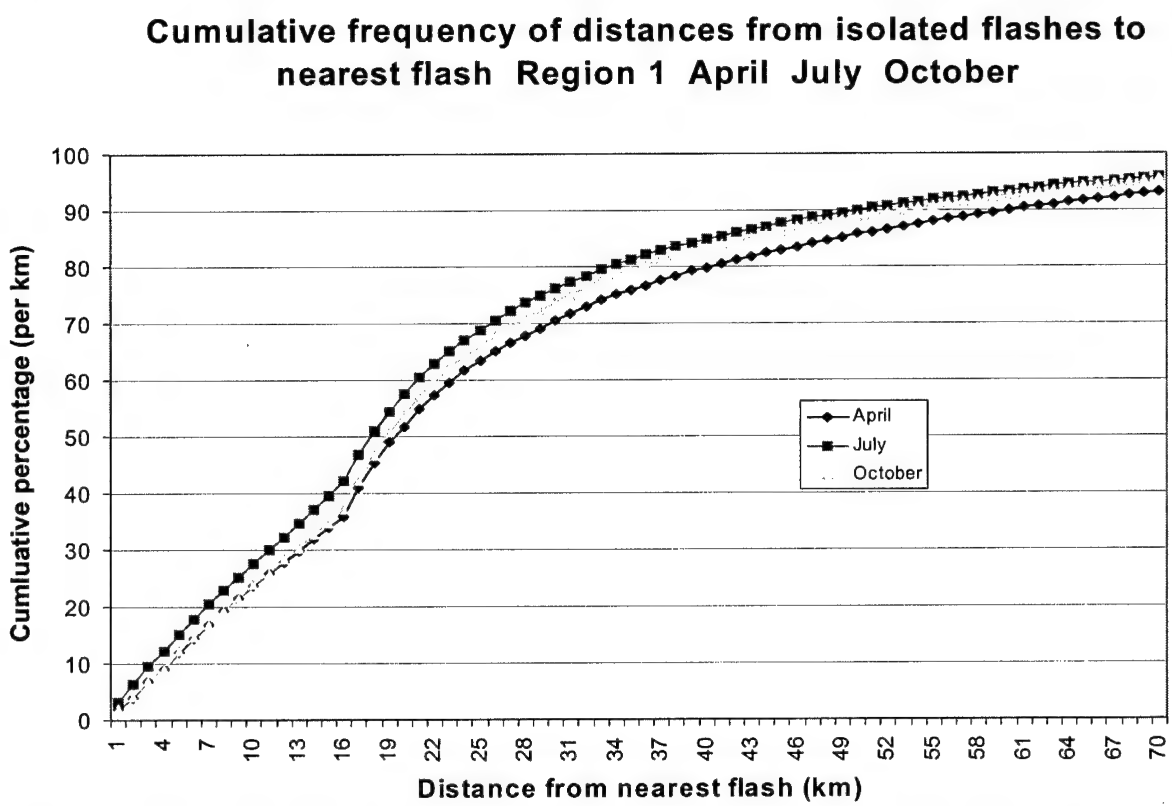

Figure C-2. Region 1 cumulative frequency distribution s of isolated flashes per km from nearest flash. Distributions for April, July, and October.

Region 2

Table C-2. Region 2 isolated flash summary statistics for individual months. Mean distance, median distance, standard deviation, variance, and the distance at the 90th percentile.

Region 2	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Total # isolated flashes	4775	7266	28190	43418	74708	66344	40781	11831	8534
Mean (km)	97.66	77.06	106.34	53.22	29.77	23.72	52.76	77.56	92.36
Median (km)	64.44	14.99	20.09	21.51	18.51	17.83	23.91	19.35	58.26
Std Dev (km)	104.67	263.01	306.23	64.59	58.65	29.52	88.42	98.55	502.33
Variance (km^2)	10956	69175	93774	1017	3439	871	7818	6072	7225
90^{th} Percentile (km)	66	65	58	50	51	53	54	54	56

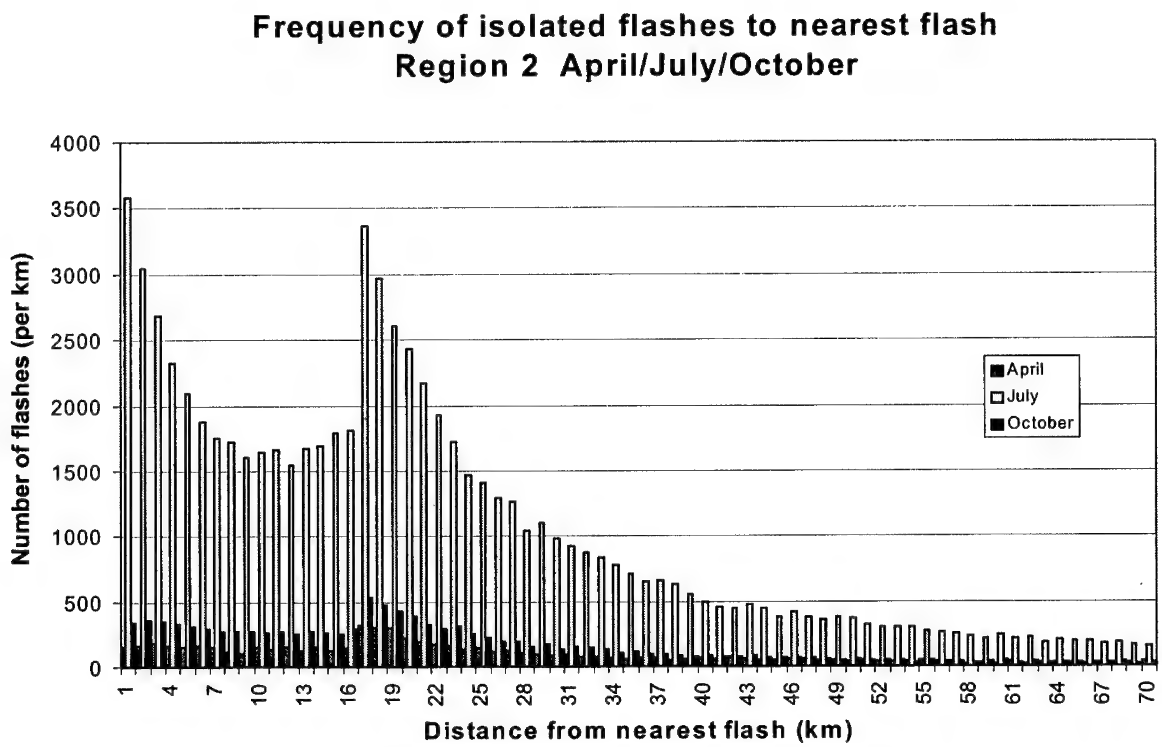

Figure C-3. Region 2 frequency distributions of isolated flashes per km to the nearest flash. Frequencies for April, July, and October.

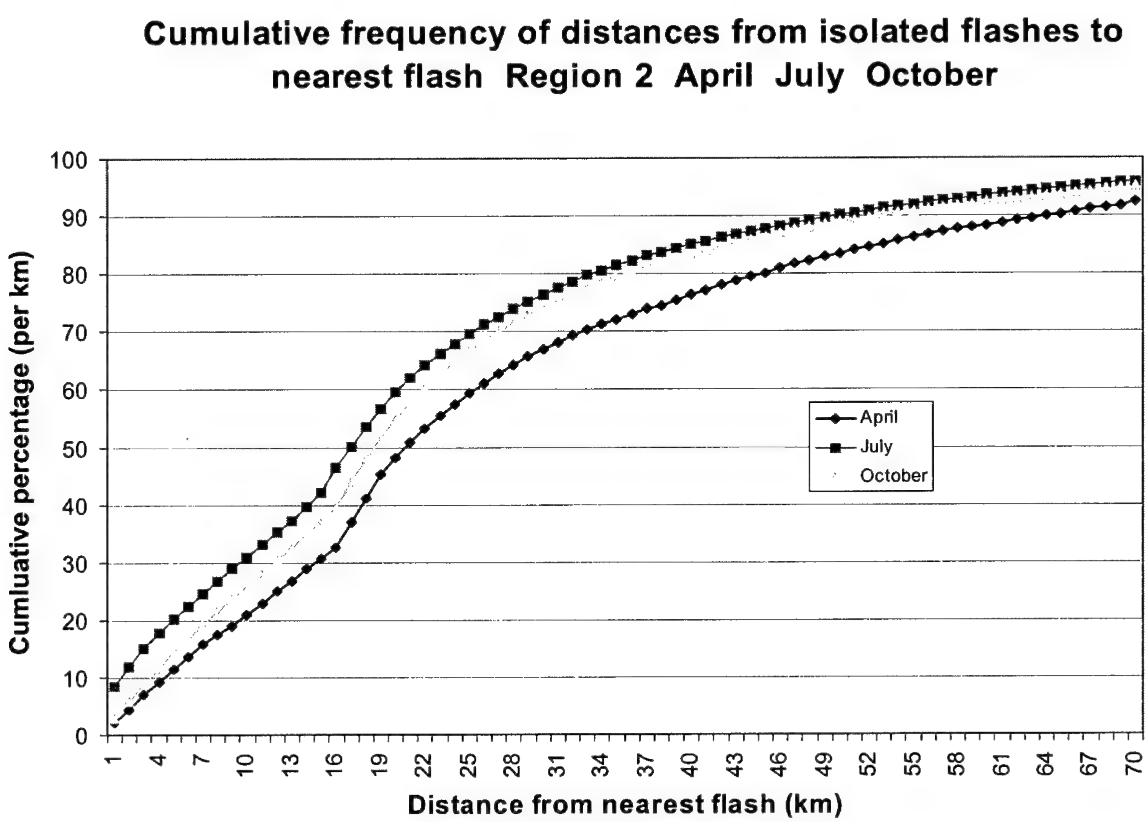

Figure C-4. Region 2 cumulative frequency distributions of isolated flashes per km from the nearest flash. Distributions for April, July, and October.

Region 3

Table C-3. Region 3 isolated flash summary statistics for individual months. Mean distance, median distance, standard deviation, variance, and the distance at the 90th percentile.

Region 3	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Total # isolated flashes	13140	26314	67585	85168	80919	66901	39628	25688	1168 0
Mean (km)	24.40	20.87	28.92	41.85	28.16	48.29	27.56	26.66	33.24
Median (km)	19.31	18.65	17.90	20.87	18.44	24.93	23.89	17.91	20.67
Std Dev (km)	24.30	17.63	65.48	79.57	40.83	119.69	19.02	32.64	58.66
Variance (km^2)	590	310	4287	6331	1667	14324	361	1065	3441
90th Percentile (km)	39	39	41	42	42	45	46	43	43

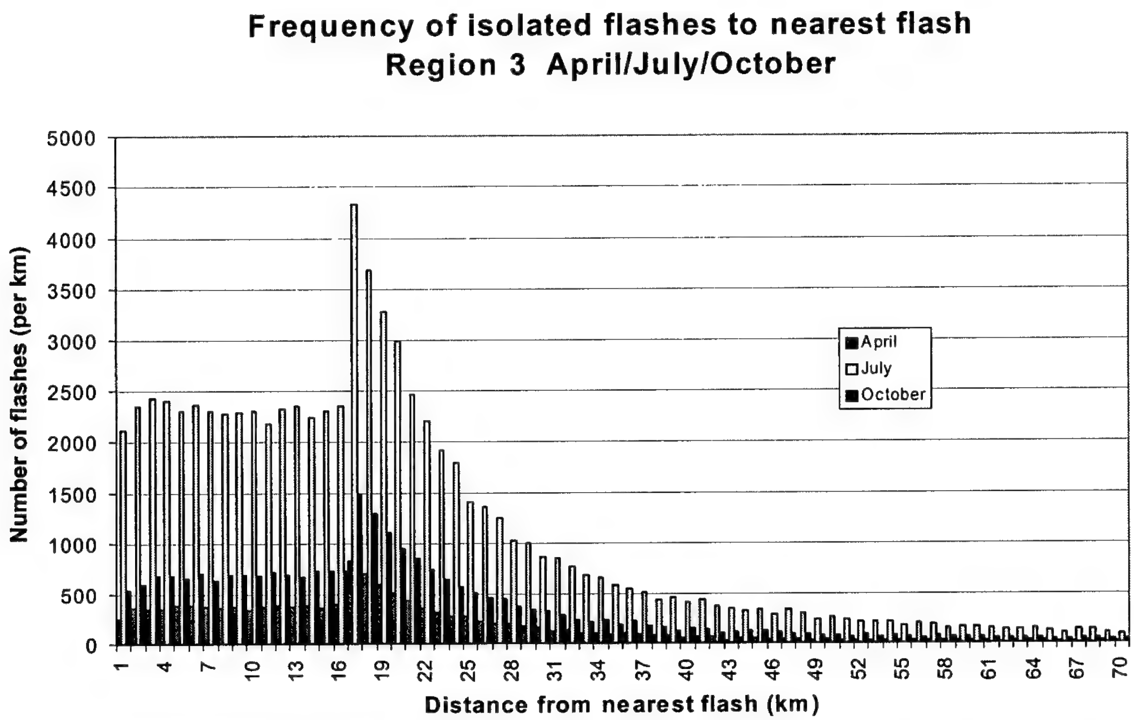

Figure C-5. Region 3 frequency distributions of isolated flashes per km to the nearest flash. Frequencies for April, July, and October.

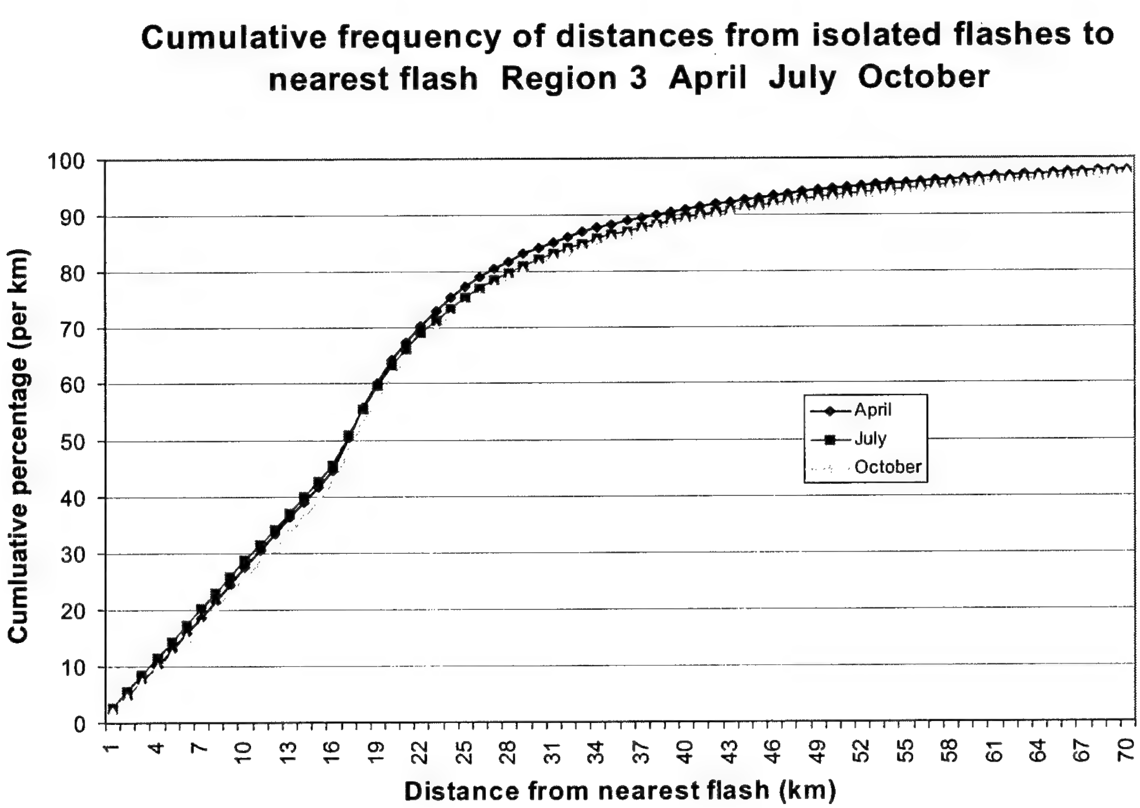

Figure C-6. Region 3 cumulative frequency distributions of isolated flashes per km from the nearest flash. Distributions for April, July, and October.

Region 4

Table C-4. Region 4 isolated flash summary statistics for individual months. Mean distance, median distance, standard deviation, variance, and the distance at the 90th percentile.

Region 4	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Total # isolated flashes	47027	59597	73167	76841	79244	67455	42448	35403	23862
Mean (km)	24.39	24.26	26.25	30.69	47.72	30.49	25.36	22.69	32.68
Median (km)	18.92	17.35	17.35	17.38	18.72	18.62	19.52	17.12	20.36
Std Dev (km)	30.43	40.11	48.08	71.85	102.67	56.94	46.23	33.00	58.86
Variance (km^2)	926	1609	2311	5162	10541	3242	2623	1088	3464
90^{th} Percentile (km)	39	37	40	47	47	51	50	44	46

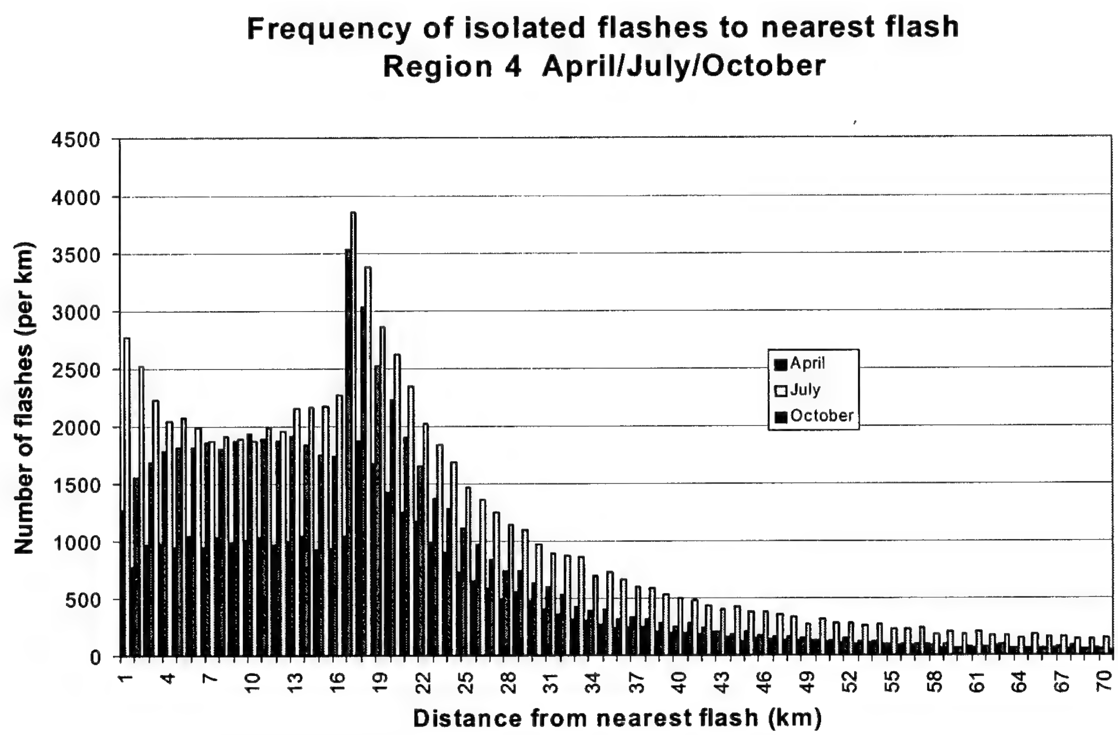

Figure C-7. Region 4 frequency distributions of isolated flashes per km to the nearest flash. Frequencies for April, July, and October.

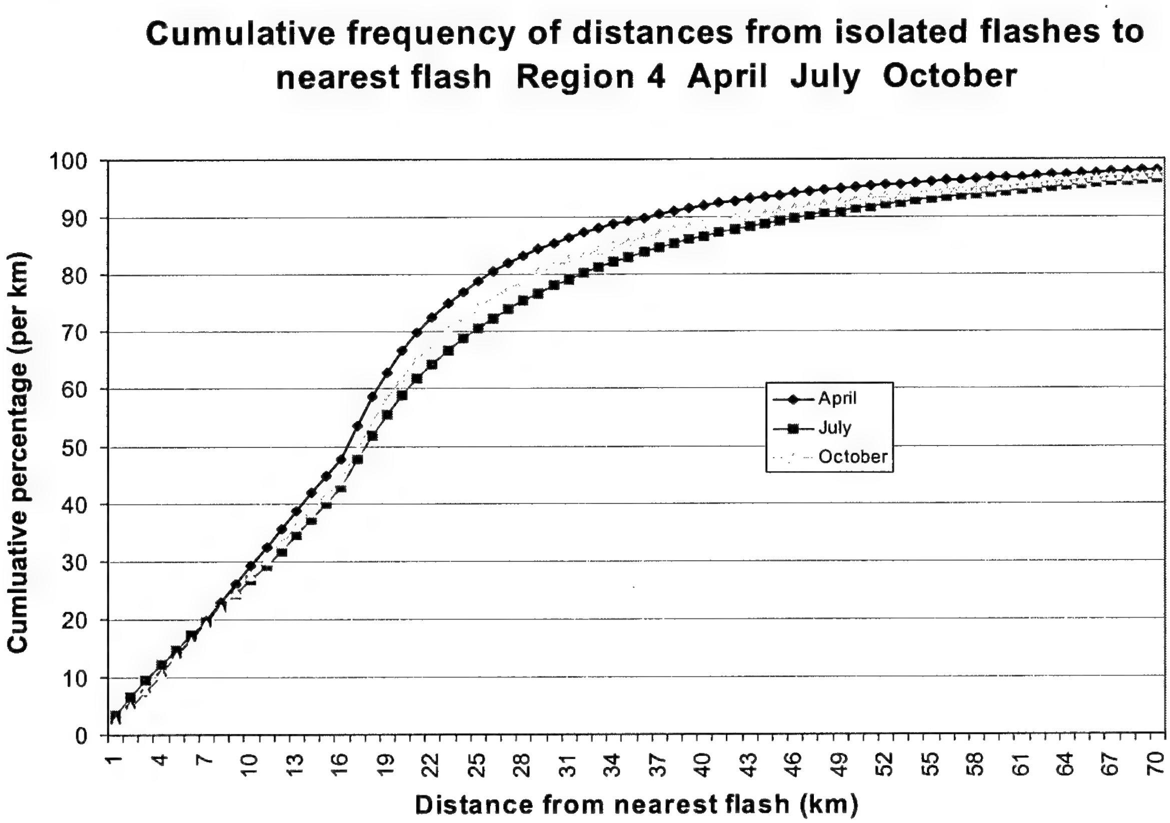

Figure C-8. Region 4 cumulative frequency distributions of isolated flashes per km from the nearest flash. Distributions for April, July, and October.

Region 6

Table C-5. Region 6 isolated flash summary statistics for individual months. Mean distance, median distance, standard deviation, variance, and the distance at the 90th percentile.

Region 6	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Total # isolated flashes	11839	33769	42115	51170	46763	23645	16567	8238	5996
Mean (km)	31.64	17.83	34.04	41.69	30.90	22.70	32.20	24.95	27.25
Median (km)	14.36	17.23	19.86	18.96	19.16	12.87	18.85	18.45	19.55
Std Dev (km)	71.25	15.29	58.41	95.59	49.12	21.76	52.95	26.92	32.40
Variance (km^2)	5076	233	3412	9137	2412	473	2803	724	1049
90^{th} Percentile (km)	39	48	41	45	47	40	50	48	48

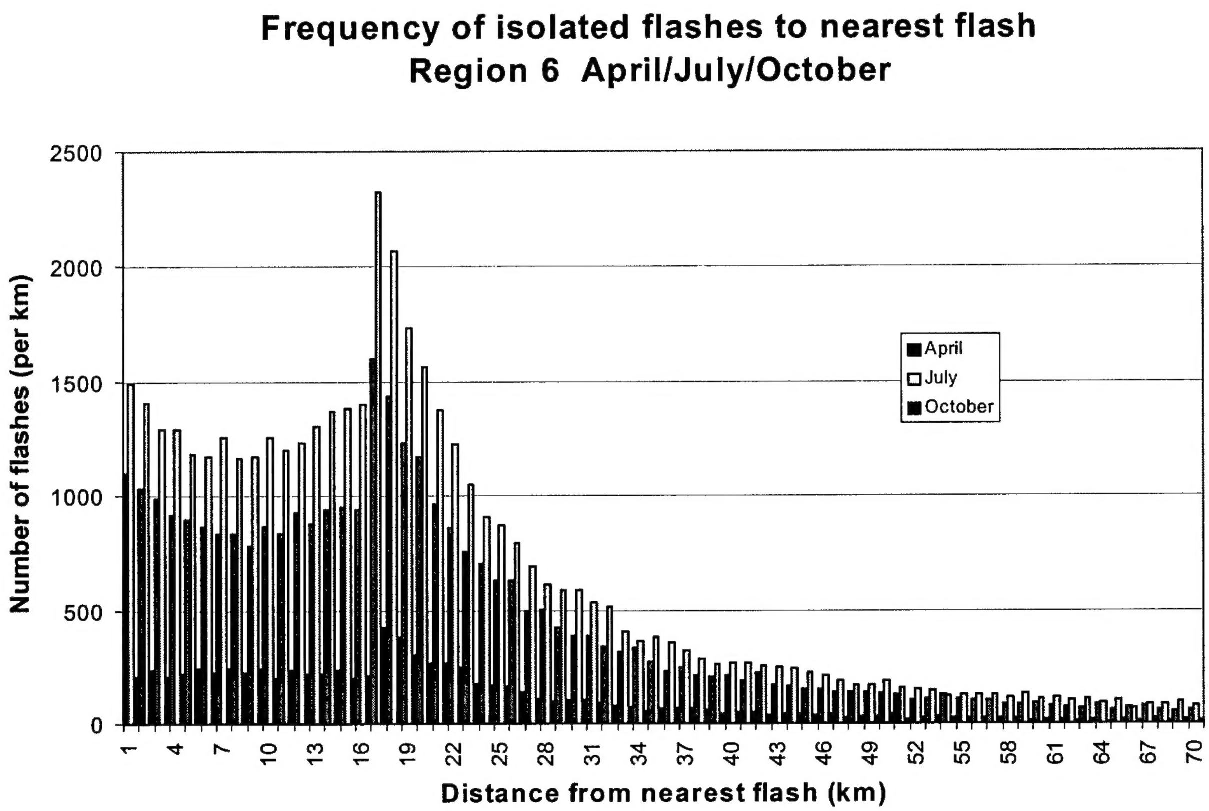

Figure C-9. Region 6 frequency distributions of isolated flashes per km to the nearest flash. Frequencies for April, July, and October.

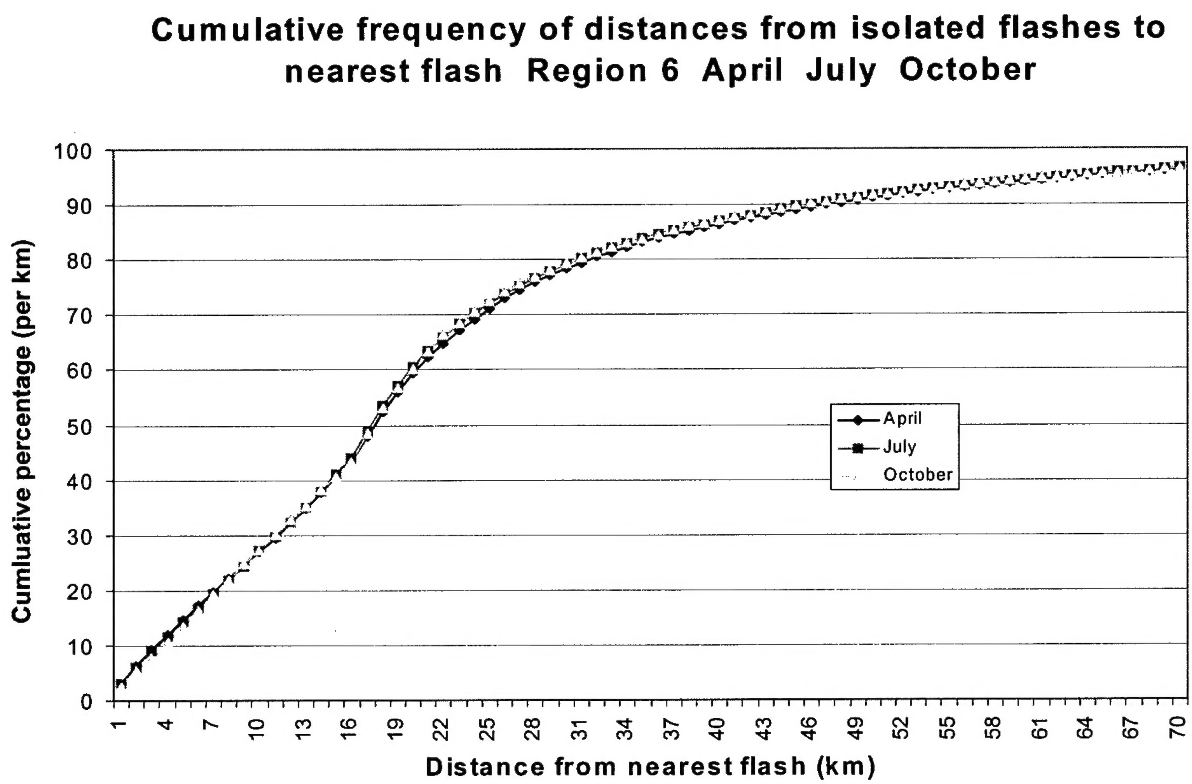

Figure C-10. Region 6 cumulative frequency distributions of isolated flashes per km from the nearest flash. Distributions for April, July, and October.

Appendix D. List of Acronyms

AFIT	Air Force Institute of Technology
AFOSH	Air Force Operational Safety Handbook
CDT	Central Daylight Time
CG	Cloud-to-ground
dBZ	Decibel
DBSF	Distance Between Successive Flash
IDL	Interactive Data Language
IMPACT	IMProved Accuracy from Combined Technology
MDF	Magnetic Detection Finders
NLDN	National Lightning Detection Network
NSSL	National Severe Storms Laboratory
SCIT	Storm Cell Identification and Tracking
TOA	Time-of-Arrival
UTC	Universal Time Code
WATADS	WSR-88D Algorithm Testing and Display System
WSR-88D	Weather Surveillance Radar – 88 Delta

Vita

Captain Tamara L. Parsons was born on 14 March 1970 in Johnson City, New York. She graduated from Montrose Area High School, Montrose, Pennsylvania in 1988 and entered the undergraduate meteorology program at The Pennsylvania State University in State College, Pennsylvania. While attending Penn State, she enrolled in the Air Force Reserve Officer Training Corps. She graduated with a Bachelor of Science degree in Meteorology and was concurrently commissioned as a 2nd Lieutenant in the United States Air Force in May 1992. While waiting to come on active duty she worked for Penn State as a research assistant on the TOGA CORE project and spent several months on the island of Kavieng in Papua New Guinea.

Captain Parsons' first assignment was to an Army Installation in Illesheim, Germany, where she became the Officer in Charge of the Cadre Weather Team. While in Germany she went on numerous deployments with the Army and participated in several NATO exercises.

Captain Parsons' next assignment took her to Vandenberg AFB, California, where she worked as a Launch Weather Officer for military, DoD, and commercial space programs. She also served as the Flight Commander, Operations Support in the 30th Weather Squadron while at Vandenberg AFB.

In August 1998, she entered the graduate meteorology program in the School of Engineering at the Air Force Institute of Technology. Following graduation, Captain Parsons will be assigned to HQ PACAF/DOWO, Hickam AFB, in Hawaii.

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13. ABSTRACT *(Maximum 200 words)*

This research effort attempted to quantify what constitutes a safe distance when lightning is present. The method used in this research project groups lightning flashes into clusters using spatial and temporal constraints. However, not all flashes meet the time and distance criteria for clustering and remained outside of the grouped flashes and as such are identified as isolated flashes. These isolated flashes are outliers in the data set, but are precisely the flashes that prove most dangerous. For this reason not only were the distances between each flash and cluster center studied, but also the distances between each isolated flash and its nearest neighboring flash. Distributions for both distances were studied for the continental U.S. by season.

A common safety radius is 5 nautical miles, just less than 9.5 km. For all regions, anywhere from 16% to 35% of clustered flashes occurred beyond 9.5 km from the cluster center and 71% to 81% of the isolated flashes occurred at distances beyond 9.5 km from the nearest flash. Cumulative frequency distributions of historical lightning data can be used to find the probability of having lightning at a particular distance. In this way an acceptable level of risk can be determined and then a "safe" distance found.

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